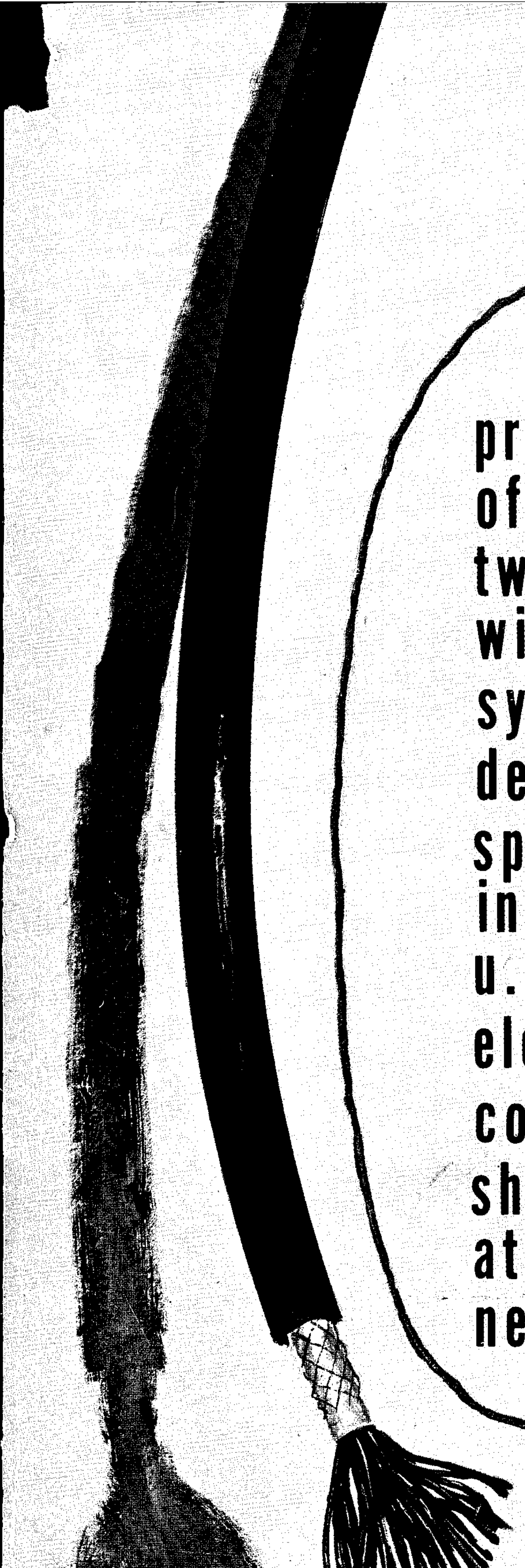

proceedings of the twentieth international wire and cable symposium

december 1971

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16195

*

Tutorial Session Notes on

CRITERIA AND REQUIREMENTS OF TELEPHONE CABLE INSULATION

by E. D. Metcalf, Anaconda Wire and Cable Company

Because telephone plant footage requirements for Exchange Area Cable are many times that of any other cable, discussion has been centered around this particular construction. It should be pointed out, however, that the same insulation is generally used for Distribution Wire and also for some Trunk Cables.

To understand the requirements of Exchange Area Cable insulation, it is necessary to have some background on the overall cable parameters. The basic important design considerations of this type of cable are as follows:

1. Controlled Electrical Characteristics
    a. Mutual Capacitance
    b. Insulation Resistance
    c. Dielectric Strength
    d. Conductor Resistance
    e. Resistance & Capacitance Unbalance
    f. Conductance
    g. Crosstalk
    h. Protection from Electrical Interference
2. Effective Packaging
    a. Water Proof
    b. Flexible
    c. Tough
    d. Resistant to Weather
    e. Resistant to Chemicals
    f. Resistant to Abrasion
3. Reasonable Cost

Basically Exchange Area Cable consists of the following general construction:

1. Conductor sizes of 19, 22, 24 and 26 AWG with insulation provided in 10 colors.

2. All conductors formed into pairs with 25 different lay lengths, each having a different color combination.

3. Pairs stranded together in basic 25 pair units to form cables. Each 25 pair unit identified by colored binders.

4. Core wrap tape applied over the stranded core for mechanical and electrical protection.

5. Aluminum or copper shield formed longitudinally over the core for protection against electrical interference. Variations in shield materials are used sometimes for added mechanical protection.

6. An outer jacket applied over the shield primarily for mechanical protection.

7. For Direct Burial, an inner jacket is usually provided under the shield to give additional protection.

Factors influencing conductor insulation can be divided into two groups - customer's needs and wire manufacturer's needs. The following customer's needs constitute the basic design requirements of the conductor insulation:

1. Capacitance: Exchange Area Cable must be designed for a system standard mutual capacitance of 0.083 microfarads per mile. For this reason capacitance is the basic criteria in insulation design and means close control of dielectric constant and insulation dimensions.

2. Insulation Resistance: To help minimize signal loss, high insulation resistance is desired to limit current leakage. Because of this, volume resistivity is checked on the raw materials and insulation resistance is checked between conductors on the finished cable.

3. Dielectric Strength: While telephone cables operate at low voltage, it is critically important that there is no breakdown between conductors. For this reason, dielectric strength is checked between conductors and to shield. High dielectric strength provides added protection in case of lightning surges.

4. Light Weight & Minimum Size: Light weight cables mean easier handling and reduced shipping costs. Density and dielectric constant are controlling factors in these characteristics.

5. Tough & Flexible: In many cases, cable installation means rough handling. Splicing may involve cramped quarters with sharp bends, tugging, scraping and compression. For this reason, tensile and elongation are standard requirements and compounds are screened for selection by abrasion and cut through tests.

6. Temperature Stability: Cable installation may be in a desert area with temperatures as high as 160°F inside the black jacket or at the other extreme of sub-zero conditions. Oven aging tests are made at elevated temperatures to insure thermal stability of the insulating material. Also, sub-zero brittleness tests and insulation cold bend tests are run to assure satisfactory low temperature handling characteristics.

7. Dimensional Stability: Stresses can be built into insulation that could cause dimensional change and termination problems with aging. While this is largely a function of processing, some materials are more susceptible to this problem than others. An aged shrink-back test is made on insulation under accelerated conditions to keep this problem under control.

8. Resistance to Chemical Attack: Insulating materials are checked for resistance to environmental chemicals such as oils, solvents, detergents and others. While the outer jacket should theoretically provide adequate protection, the insulation can easily come in contact with pulling compounds, solvents, etc. in terminating. An environmental stress crack test is required for the insulating material using a cracking agent, Igepal, under accelerated conditions.

9. Clear, Consistent and Permanent Colors: The 25 paired color combinations must be easily identifiable under adverse conditions, such as in a manhole, and also upon splice re-entry after installation for many years. Insulation colors are required to meet Munsell color standards with close tolerances and are tested for permanence of color and migration after accelerated aging.

10. Stability in Water: While insulated conductors are not expected to operate in water, jacket ruptures, storms, etc., occasionally result in such a condition. Because some insulating materials are susceptible to electrical deterioration in water, an insulation resistance test is run on insulated conductors in water both before and after an extended immersion period.

11. Long Life: Telephone Plant generally is installed with a life expectancy of 30 years. Accelerated aging tests are run at various elevated temperatures and deterioration is plotted against time, based on the Arrhenius Equation. The life of the insulation is then predicted by extrapolating the curve for the expected installed temperature.

Besides the insulation requirements that are necessary to meet the needs of the cable user, there are also characteristics that are important to efficient manufacturing. Some of these are as follows:

1. Material Uniformity: Uniformity of pellet size and consistency between batches is important in color control and processing. Also, wide variation in pellet size between manufacturers may mean different color meter settings and process changes.

2. Moisture Content: Excessive moisture in insulating material can result in surface roughness or other extrusion problems. While most compounds used for this insulation absorb very little moisture, precautions should be taken in packaging and handling to control this condition.

3. Compatibility with Other Compounds: Since most manufacturers find it desirable to have more than one material supplier, it becomes important that compounds are compatible at change-over. Complete, 100 percent clean-out of storage silos and equipment can be costly.

4. Compatibility with Cable Components: Insulating compounds must not react with other materials in the cable such as the copper conductor, filling compounds, etc. Exhaustive long term screening tests are run on such combinations to assure component stability.

5. Easy Processability: Compounds must be capable of repeated runs with standardized extruder conditions. The sensitivity range should be broad enough that room temperature changes, gauge sizes, etc., do not cause problems. Flow properties should allow high speed extrusion at 5,000 or 6,000 feet per minute.

6. Low Extrusion Drag Rate: Conductor resistance is critical in finished cable and is effected by amount of draw down in extrusion. Compound flow characteristics that provide a minimum drag on the copper assist in maintaining low resistance unbalance in a pair.

7. Low Fault Rate: Compounds should be free from dirt, gels or other foreign materials which would produce pin holes or weakened dielectric strength. All insulation is spark tested for voltage breakdown.

8. Cut-through Resistance: Because of the high processing speeds and the thin wall of insulation, resistance to cut-through at pressure points is extremely important. Automatic reel change-over equipment, reel traversing guides, transfer sheaves, etc., all contribute to the need for tough insulation.

9. Abrasion Resistance: Pulling insulated wire through twinner bows, strander guide eyelets, etc. may cause surface abrasion in high speed handling. For this reason, low surface friction and resistance to abrasion are both important factors in selecting insulating materials.

The above list of customer's and manufacturer's needs define the major requirements for Exchange Area Cable insulation. However, since this information has been presented as a general guide for those not intimately associated with the telephone cable industry, some of the more complex facets of design have been purposely simplified or omitted.

A. J. REAPPY
PLASTEC
Picatinny Arsenal
Dover, N. J. 07016

PROCEEDINGS OF 20th INTERNATIONAL WIRE AND CABLE SYMPOSIUM

Sponsored by Industry and U. S. Army Electronics Command

Atlantic City, N. J.

November 30–December 2, 1971

Approved for Public Release; Distribution Unlimited

16194 – # 16211

DEPARTMENT OF THE ARMY
HEADQUARTERS UNITED STATES ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY 07703

30 November 1971

To All Our Participants:

It is a pleasure to extend this official welcome to the Twentieth Annual International Wire and Cable Symposium.

It is gratifying to note the unique growth of this joint US Army/ Industry-sponsored symposium . . . from the first informal meeting in 1952 of some fifty interested engineers, to the current international symposium with attendance of over one thousand personnel from sixteen nations. This annual meeting has become a major forum for the exchange of information on new materials, processing technologies, advanced designs and the latest application in the field of military wires and cables.

The Department of the Army continues to be critically dependent on electronics for future weapons and next generation communication systems . . . with the inevitable demand for still higher performance levels and new requirements. I am confident that the Wire and Cable Industry will meet these new challenges with the same enthusiasm and creativity that it has shown in the past.

Congratulations to you and your symposium committee for reaching this twentieth milestone year. My best wishes for your continued success in the years ahead.

HFFoster

HUGH F. FOSTER, JR.
Major General, USA
Commanding

20th INTERNATIONAL WIRE AND CABLE SYMPOSIUM

SYMPOSIUM COMMITTEE

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Jack Kirk, Alberta Government Telephones
Louis J. Frisco, Raychem Corp.

TECHNICAL SESSIONS

Tuesday, 30 November 1971

9:30 a.m. Session I:	Tutorial Session on "Insulating and Jacketing Materials and Application to Telephone Cable" NOTE: Lectures will not be published—Notes will be handed out at the session
2:00 p.m. Session II:	Coaxial Cable for PCM and Broadband Transmission

Wednesday, 1 December 1971

9:30 a.m. Session III:	Conductors, Insulated Wire and Assemblies
2:00 p.m. Session IV:	Manufacturing Techniques and Processes for Communication Cable

Thursday, 2 December 1971

9:30 a.m. Session V:	Telephone Cable Materials
2:00 p.m. Session VI:	Cable Design, Testing and High Voltage Characteristics

PROCEEDINGS

Responsibility for the contents rests upon the authors and not the Symposium Committee or its members. After the symposium all the publication rights of each paper are reserved by their authors, and requests for republication of a paper should be addressed to the appropriate author. Abstracting is permitted, and it would be appreciated if the symposium is credited when abstracts or papers are republished. Requests for individual copies of papers should be addressed to the authors. Extra copies of the Proceedings may be obtained from the Symposium Co-Chairman (Requests should include a check for $5.00 per copy, made payable to the Shelburne Hotel). Copies may also be obtained for a nominal fee from the National Technical Information Service (NTIS), Operations Division, Springfield, Virginia 22151.

Copies of papers presented in previous years may also be obtained from the National Technical Information Service. Papers from the first 20 years, with their AD numbers are cataloged in the "KWIC Index of Technical Papers, Wire and Cable Symposia (1952-1971)," December 1971.

MESSAGE FROM THE CO-CHAIRMEN

It has been our pleasure to serve as co-chairmen of the symposium committee since 1964. During these past eight years we have been most gratified by the enthusiasm and cooperation of the committee members who have worked so diligently in the planning and conduct of these symposia. The quality of the technical papers has been most rewarding and the key element to the continued growth of this symposium. The selection of outstanding papers for awards among the many worthy of recognition has always been a very difficult task. To all those unsung authors, our deep appreciation.

No symposium can really prosper without the sustained participation and attendance of representatives of the various industrial organizations and government activities. This continued support and financial sponsorship has nourished this meeting from its meager beginnings in 1952 to the present prestigious place in the worldwide wire and cable community.

Our committee continues to look for ways to improve the activities of the symposium. We are constantly exploring innovations for technical growth and to promote the interchange of information as well as to provide a convivial environment at a nominal cost to the sponsors and attendees.

The ultimate credit for this success belongs to a lengthy list of people who so ably served on the symposium committee. On the occasion of our twentieth anniversary we are happy to salute them and inscribe their names on the accompanying honor role.

Jack Spergel

M J Mayer

Honor Roll

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1969-70 — F. Oberlander, RCA Corporation
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1970-71 — D. Stewart—Phillips Petroleum Company
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1971 — J. Kirk—Alberta Government Telephones
1971 — L. J. Frisco—Raychem Corporation
1963 — M. Tenzer—U. S. Army Electronics Command
1963 — J. Spergel—U. S. Army Electronics Command

HIGHLIGHTS OF 19th INTERNATIONAL WIRE & CABLE SYMPOSIUM

1, 2, and 3 December 1970

Shelburne Hotel, Atlantic City, N. J.

W. L. Doxey, Associate Directorate for Research, Development & Engineering, USAECOM, welcoming the attendees at the banquet.

Certificates of Appreciation presented by M. Tenzer (center) to F. Oberlander, RCA Corp., and J. Ruskin, Phillips Cables, Ltd., for serving on the committee.

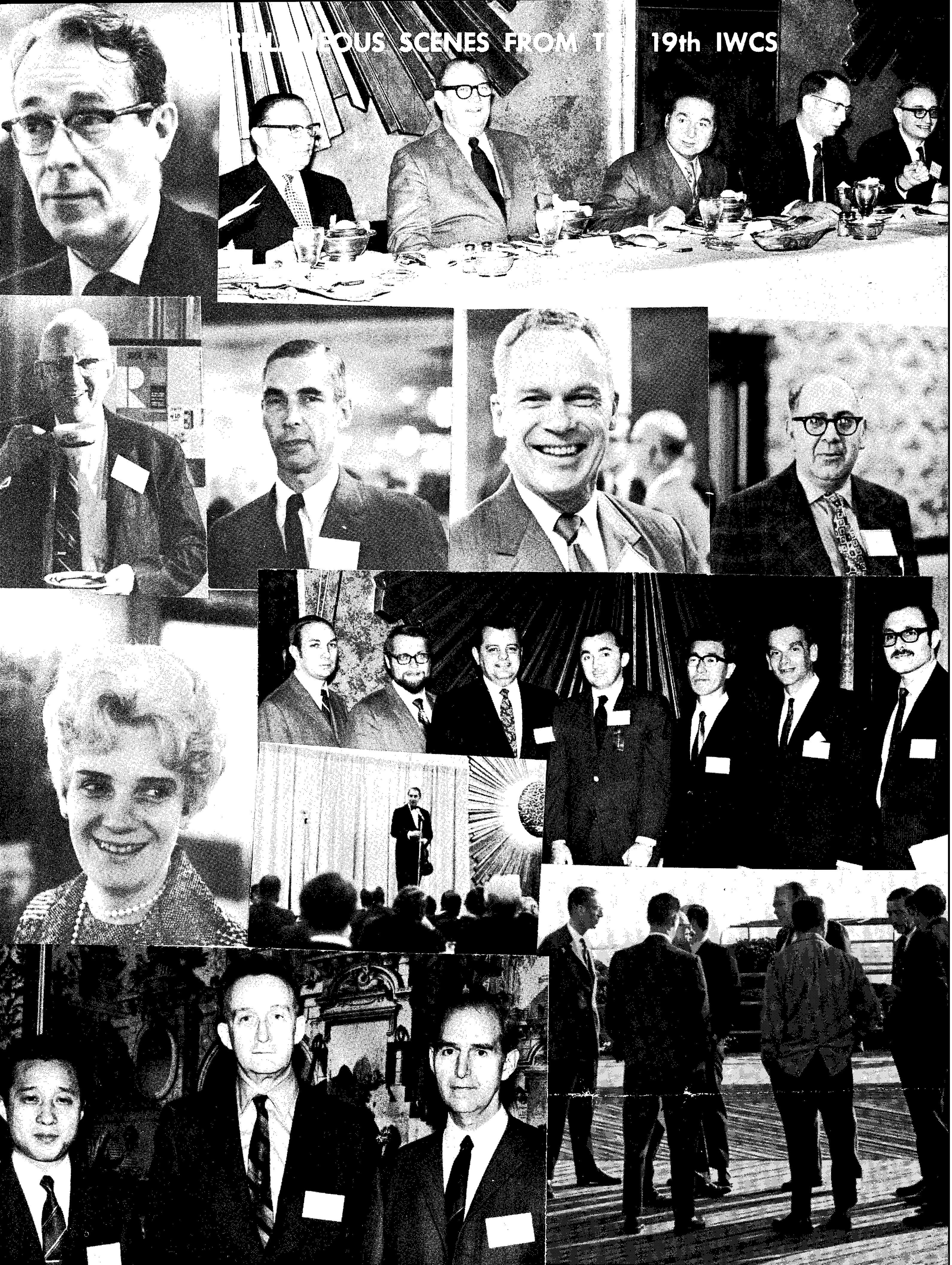
Award for Best Technical Paper: R. Sabia, B. Wargotz, J. P. McCann, B. T. L., receiving plaques from J. Spergel for their outstanding paper entitled "Characterization of Filler and Insulation in Waterproof Cable" at the 18th IWCS.

Award for Best Presentation of a Technical Paper: R. Brooks, AGT, receiving plaque on behalf of J. Kirk, AGT, from J. Spergel for best presentation of a significant technical paper entitled, "Progress and Pitfalls of Rural Buried Cable."

CANDID SCENES FROM 19th IWCS

The photos on this and succeeding pages were provided through the courtesy of USAECOM Wire & Wire Products and Carroll McKenna

MISCELLANEOUS SCENES FROM THE 19th IWCS

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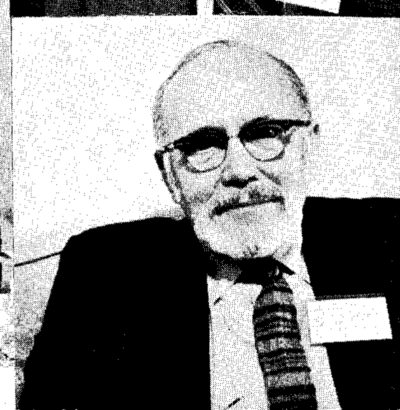

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Trenton, New Jersey

Zumbach Electronic-Automatic
Nyack, New York

x in system

TABLE OF CONTENTS

TECHNICAL PROGRAM

Tuesday, 30 November 1971, 9:30 a. m.

SESSION I — Tutorial Session on Insulating Materials and Application to Telephone Cable

Chairman: Jack Spergel, U.S. Army Electronics Command

"Insulating Material Parameters and Their Functional Relation to Cable Design," *by J. R. Perkins, E. I. Dupont de Nemours & Co., Inc.*

x "Criteria and Requirements for Insulating Materials Used in Telephone Cable," *by E. Metcalfe, Anaconda Wire & Cable Co.* 16195

(NOT PUBLISHED)

Tuesday, 30 November 1971, 2:00 p.m.

SESSION II — Coaxial Cable for PCM and Broadband Transmission

Chairman: J. D. Kirk, Alberta Government Telephones

x "An Advanced Multi-Unit Coaxial Cable for Toll PCM Systems," *by R. McClean, T. McManus, Bell-Northern Research, and R. Iyengar, Northern Electric Co., Ltd.* .. 1 16196

"Development and Practical Application of 375 Type 18 Core Coaxial Cable and Associated Accessories," *by H. Fukutomi, Nippon Telegraph & Telephone Public Corp., and M. Sato and H. Shioyama, Sumitomo Electric Industries* 24

x "Fused Disc Coaxial for Broad Band Transmission," *by H. Lubars, L. Jachimowicz, and J. Olszewski, General Cable Corp.* 34 16197

"A New Coaxial Cable for PCM Systems," *by G. Fuchs and R. Mathieu, Societe Anonyme De Telecommunications* 53

x "Broad-Band Leaky Coaxial Cable with Small Size Coaxial Cables in Its Center Conductor," *by K. Mikoshiba, T. Hanaoka, Hitachi Cable, Ltd., and T. Kishimoto, T. Yaku, Japanese National Railways* 61 16198

Wednesday, 1 December 1971, 9:30 a.m.

SESSION III — Conductors, Insulated Wire and Assemblies

Chairman: L. J. Frisco, Raychem Corp.

x "Dielectric Properties Testing of Insulation on Wire/Cable Common to the Aerospace Industry," *by R. L. Gilworth and C. F. Louis, McDonnell Aircraft* 67 16199

x "Parameters Affecting the Ability of Insulation on Solid Conductor Wire to Withstand Cut-Through," *by E. F. Timpane, General Electric Co., and W. D. Watkins, U.S. Naval Avionics Facility* 77 16200

"Thermal Aging of Tin Coated Copper Conductors," *by Dr. D. J. Larson, G. A. Busch, J. H. Burns, Grumman Aerospace Corp., and L. J. Frisco, N. C. Enault, Raychem Corp.* 89

x "A New Flame Resistant Chemically Cross-Linked PVC Insulation—Flamenol® XL," *by J. E. Betts and Dr. M. Prober, General Electric Co.* 98 16201

x "Mimi—A Lightweight, Small Volume Electrical Interconnect Harness for the F-15," *by R. Soloman, McDonnell Aircraft Co.* 110 16202

"The Design of Cable Connector Combinations to Achieve Electromagnetic Interference Control," *by D. E. Clark, Bendix Corp.* 118

Wednesday, 1 December 1971, 2:00 p.m.

SESSION IV — Manufacturing Techniques and Processes for Communication Cable

Chairman: E. Mark Wolf, Anaconda Wire & Cable Co.

"Vacuum-Pressure Impregnation of Waterproof Cable and Associated In-Line Compound Mixing System," *by R. G. Schneider and E. L. Franke, Western Electric* 134 16203

"Prefabricated Pressure Dam for Telephone Cable," *by H. Fukutomi, K. Ogawa and J. Egashira, Nippon Telegraph and Telephone Public Corp.* 140 16204

"SZ Twisting and Stranding of Communications Cables Using Rotating Accumulators with Periodically Changing Capacity," *by D. Vogelsberg, Siemens (Berlin)* 145

"Multi-Paired Cable of Non Layer Design for Low Capacitance Unbalance Telecommunication Networks," *by S. Nordblad, Telefonaktiebolaget L M Ericsson*... 156

"New Type Paired Cable for High Speed PCM Transmission," *by N. Kojima, M. Taguchi, M. Ohmura, Ibaraki Electrical Communication Lab N.T.T.* 164

Thursday, 2 December 1971, 9:30 a.m.

SESSION V — Telephone Cable Materials

Chairman: D. Stewart, Phillips Petroleum Co.

"A New Foamed Polyethylene Insulated Junction Cable for Telecommunication," *by S. Tanaka, A. Tsujikawa and H. Ishihara, The Fujikura Cable Works, Ltd., and K. Ogawa, Nippon Telegraph & Telephone Public Corp.* 183 16205

"Pure Aluminum Conductors in Fully Filled Cellular Polyethylene Insulated Telephone Cables," *by P. Patout, Trefimetaux* 194 16206

"Evaluation of Thermal Degradation in Polyethylene Telephone Cable Insulation," *by B. Pusey, M. Chen and W. Roberts, Superior Continental Corp.* 209 16207

"Long Term Stability of Polyethylene Insulated Fully Filled Telephone Distribution Cables," *by S. Verne, R. T. Puckowski and A. A. Pinching, B.I.C.C.* 218 16208

"An All-Aluminum Conductored Telephone Exchange," *by R. Neal,* Anaconda Wire & Cable Co. 229

"Application Techniques and Accessories for Filled Communications Cable," *by J. Lyon, Anaconda Wire & Cable Co.* 235 16209

Thursday, 2 December 1971, 2:00 p.m.

SESSION VI — Cable Design, Testing and High Voltage Characteristics

Chairman: M. M. Suba, Union Carbide

"Walt Disney World Contemporary Cable System," *by P. J. Hartling, WED Enterprises, and W. L. Sellers, General Cable Co.* 243

"The Uni-Field Flat Cable, A New Multisignal Transmission Line," *by J. B. Marshall, Ansley Electronics Corp.* 244

"Advances in Automatic Computer Controlled Measurements of Cable Parameters," *by P. P. Jorrens, General Radio Company* 257

"High Frequency Power Breakdown of Coaxial Cables," *by G. Rodriguez, Naval Ship Research & Development Center* 263 16210

"The Effect of Lightning Arcing Currents on Telephone Cables," *by the late W. Bishop, E. Fisher and E. Kelch, Rural Electrification Admin.* 285 16211

"Lightning Induced Current Surges on a Buried Multi-Coaxial Cable System," *by D. A. Douglass, Bell Telephone Labs*........ 293

"Electro-Magnetic Interference with Video Transmission Cable," *by S. Inao, H. Hondo and Dr. H. Murata, Furukawa Electric Co., Ltd.* 309

"Computer Aided Design of Braid Parameters for Coaxial Cable," *by J. Spergel, U.S. Army Electronics Command* 319

AN ADVANCED MULTI-UNIT COAXIAL CABLE FOR TOLL PCM SYSTEMS

R. McClean *and* T. McManus
Bell-Northern Research

R. Iyengar
Northern Electric Co. Ltd.
Montreal, Quebec

ABSTRACT

This paper reviews some of the physical and electrical problems encountered with multi-unit coaxial cables, particularly during installation, and the design, process development and material investigation associated with the development of a new laminated-corrugated coaxial unit for broadband application. The computer programme used in the evaluation of the unit and the production facilities are also described. The coaxial unit is shown to produce, in combination with a corrugated steel sheath, a physically rugged cable of toll quality, primarily for pulse code modulated systems, but also analogue systems of the higher frequency category.

INTRODUCTION

Prior to 1964, the use of multi-unit coaxial carrier cable in Canada was limited to wire line entrance links connecting the major urban centres with the microwave radio system.

During the early nineteen-sixties, it became evident that a coaxial cable system could compete with radio or paired carrier cable systems, if more competitive cable designs could be obtained. Furthermore, if mechanical, or more specifically, plowing methods of installation were also feasible, additional economic advantages could be realized in many areas.

In evaluating existing designs for this application, the use of solid dielectric coaxial units was considered, and rejected for economic reasons. The semi-air dielectric units available at that time were also considered and rejected, again primarily because of cost, but to some extent because of the relatively fragile nature of the product. Subsequently, an expanded (cellular foam) polyethylene insulated coaxial unit was selected and modified for carrier use. This expanded coaxial design proved very successful with a 240 channel carrier system operating in the 60 to 1,052 kHz range.

A proposal aimed at increasing the capacity of the system on this cable to 1200 or more channels highlighted the attenuation stability of chemically expanded dielectrics[1] and the critical nature of attenuation stability in a long distance analogue system. While the predicted attenuation variations could have been accommodated electronically, the economic penalty thus borne by the line equipment made such a proposal unattractive.

It was apparent therefore, that if a coaxial system was to be competitive, and the cable take advantage of mechanical methods of installation, a new semi-air dielectric coaxial unit would have to be developed.

This paper deals with the physical and electrical evaluation of various cable designs, the subsequent development of a physically rugged coaxial unit and its use with a sheath of similar characteristics.

INITIAL EVALUATION

One problem encountered when a coaxial cable is installed, is the change in impedance which can occur in the coaxial unit during the installation operation. An example of the cause of such a change is the compressive force which is exerted on the sheath between the guide chute and the soil when the plow changes direction. The extent of such an impedance change depends on the margin of safety between the forces which are encountered during installation, and the force on the cable which will result in an impedance change in the coaxial unit.

While some of the impedance changes of the type encountered can go undetected by conventional means of carrier cable evaluation, they can have a significant effect on the more sophisticated analogue and digital systems of the future. How such impedance changes are detected, and their significance evaluated, depends on a number of interrelated factors, ranging from test equipment, location and severity of the discontinuity, and the characteristics of the specific system. This is in some respects beyond the scope of this paper.

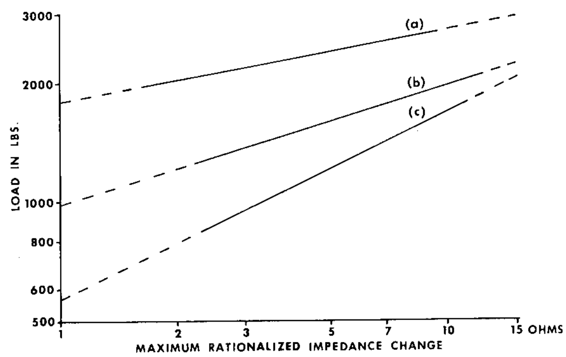
A laboratory and field evaluation was carried out to determine the magnitude of the forces involved and their effect on the impedance of the coaxial units.

In the laboratory stage of this program, discrete impedance variations were evaluated using Time Domain Reflectometer (TDR) techniques. In the field, TDR tests were supplemented by structural return loss (SRL) and standard pulse echo measurements.

Laboratory Tests

The laboratory study evaluated the effect on the coaxial units of a steady compressive stress and an impact force, when applied to various composite sheaths.

In the compressive stress tests, the ARPASP sheath was found to withstand a much greater force than a PASP sheath with a core of identical construction. A similar core, when protected by a corrugated steel sheath, had no electrical deterioration until the compressive force was at least double that applied to the PASP sheath. Fig. 1 demonstrates this effect on three 8-unit 375 designs.

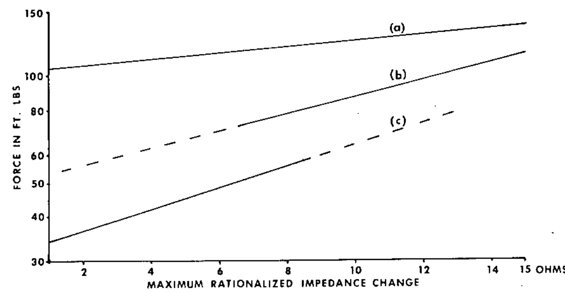


(a) 8-Unit Corrugated Steel Sheath
(b) 8-Unit ARPASP Sheath
(c) 8-Unit PASP Sheath

FIG. 1 THE EFFECT OF A COMPRESSIVE FORCE OVER A 6" LENGTH OF 8-UNIT .375" SERRATED SEAM COAXIAL CABLE

The effect of an impact force reflects an even greater relative difference between the various designs. See Fig. 2 for measurements on the same three 8-unit 375 designs.

The above impedance changes were detected using a 150 p. second step function. The manner in which the force could be distributed between the coaxials, under the applied load, was resolved[2] by assuming that each impedance change recorded was a VECTOR radiating from the centre of the cable through the coaxial unit in question. The vector sum of all impedance changes was calculated in each direction, omitting negative values from the calculation, and the maximum value used for comparative purposes. The summation of all impedances was named the rationalized impedance.

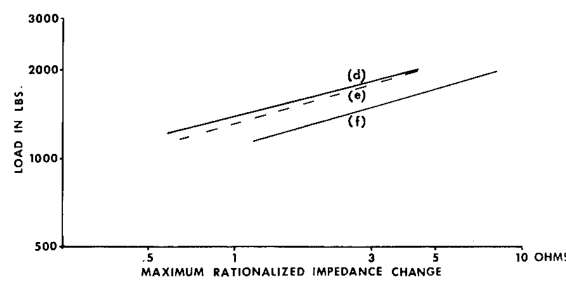


(a), (b) and (c) as in FIG. 1

FIG. 2 THE EFFECT OF IMPACT ON 3" LENGTH OF 8-UNIT .375" SERRATED SEAM COAXIAL CABLE

In addition to the different impeance changes which were produced by an identical force on cable sheaths with similar cores, the impedance changes were also found to be diameter dependent.

A comparison is made in Fig. 3 between an 8-unit and a 12-unit 174 coaxial with concentric coaxial unit lay-ups and an ARPASP sheath.



(d)	*8-Unit Design (Actual)*	*Diam.*	*1.3"*
(e)	*8-Unit Design (Theoretical)*	*"*	*1.3"*
(f)	*12-Unit Design Actual*	*"*	*1.6"*

FIG. 3 THE EFFECT OF A COMPRESSIVE FORCE OVER A 6" LENGTH OF .174" COAXIAL CABLE

It can be seen from Fig. 3 that a decrease in diameter resulted in a relative improvement in the sheath crush resistance. The theoretical curve for the 8-unit design is shown relative to the 12-unit design, based on the following relationship:-

$$Z_2 = Z_1 \cdot \frac{t_1^3}{D_1^3} \cdot \frac{D_2^3}{t_2^3} \quad \ldots\ldots\ldots\ldots \quad (1)$$

This assumes that the numerical deflection in each sheath is proportional to the same rationalized impedance change. From the limited data available this appears to be a valid assumption.

This expression was derived from the expression:-

$$\text{Load} = \text{Constant} \times \frac{t^3}{D^3} \times \text{Youngs Modulus} \times [\text{Deflection}$$

Hence comparing similar constructions we have, for the same load,

$$\text{Deflection}_1 \frac{t_1^3}{D_1^3} = \frac{t_2^3}{D_2^3} \text{Deflection}_2$$

D_1 = Outside diameter of the original sheath
D_2 = Outside diameter of the new sheath
t_1 = Proportional thickness of the original sheath wall
t_2 = Proportional thickness of the new sheath wall
Z_1 = Maximum rationalized impedance of the original design
Z_2 = Maximum rationalized impedance of a similar design

Field Tests

To obtain an appreciation of the forces exerted on a cable during installation, a cable plowing field trial was made to supplement the laboratory tests. This trial was conducted on ideal plowing terrain in an attempt to eliminate any random effects due to underground obstructions. The plow selected had a 5 ft. radius chute designed specifically for direct burial of 4" duct. Five cable designs were put through similar plow manoeuvres involving gradual and sharp turns (approx. minimum radius 8 ft.), raising and lowering the chute, etc., to simulate actual operating conditions.

Electrical measurements were taken before, during and after each cable installation, to evaluate the effect of the plow and its various guide components on the cable. Table I is a simplified summary of the results on three 8-unit .375" coaxial designs with similar core constructions but different sheaths. The core/unit design of the corrugated steel design differed slightly from the other two cables and probably accounted for the minor impedance changes detected at the lay frequency. No impedance change was detected in this latter cable due to an external force.

In addition to the 8-unit cables, a 4-unit .174" PASP sheathed cable was successfully installed, while an 18-unit .375" Stalpeth was found to be unsatisfactory.

Neglecting some problems with the plow/cable guide system, which were subsequently rectified by equipment modifications, all major points of trouble in the cable occurred where the plow changed direction.

While a direct correlation was not possible between the various cable designs after plowing, due to differences in the actual plow manoeuvres, there is little doubt from the readings taken that compressive forces of less than 1000 lbs. were developed across the ARPASP design, while forces in the order of 1500 lbs. were encountered by the PASP design. Since it is unlikely that the initial force impressed on any one cable was greater than that on the other, it is felt that the soil was softer than the ARPASP sheath, and thus gave slightly under the load. In the PASP case the sheath was the softer component and deformed under the load. If this is the case, the laboratory results should only be taken as an indication of the relative performance of the cables. In practice the differential will be greater than shown until the hardness of the soil

TABLE I

Sheath	Worst Corrected Echo (Pulse Width 125 and 63 n sec.)		Comment	Time Domain Reflectometer Impedance Change	S.R.L. Values Worst Value From 7-220 MHz	
	Original	Final			Original	Final
	dB		dB	ohms	dB	
PASP	Avg. 66 Range 64-69	55 47-67	Degraded -11	Average 1.9 Maximum 9.2	29	11.5
ARPASP	Avg. 66 Range 59-72	68 62-74	Similar +2	Average 0.12 Maximum 0.36	35	33
Corrugated Steel	Avg. 66 Range 64-76	73 71-76	Improved +7	Average 0.08 Maximum 0.1	27.5	25

exceeds the resistance to crush of the most resistant sheath being considered. At this point the laboratory results would be comparable with field performance.

It was concluded at the end of the laboratory/field evaluation that; (i) with some modification to plow equipment and installation procedures, an ARPASP design would have a reasonable margin of safety for the smaller diameter coaxial cables, and (ii) a more rugged cable construction was needed for the larger cables to improve the margin of safety. As a result of the preceding evaluation and related work on coaxial units, a two part program was approved to satisfy the immediate and future coaxial system needs.

The first part of the program was completed in 1970 with the successful installation of 34 miles of 12-unit .174" coaxial ARPASP cable in the vicinity of Calgary, Alberta. The majority of this cable was installed by a plow developed using the experience gained during the field trial. Fig. 4 is a photograph of the plow. In this installation the *worst* corrected echo per unit per repeater section in the plowed portion ranged from 52 to 69 dB. 228 readings were taken, the average worst value was 60 dB and the standard deviation 3.6 dB.

The second part of the program, which started in 1967, is the main subject of this paper and covers the development of a multi-unit coaxial cable for a high capacity PCM system. This cable is intended to meet, economically, the future long haul toll needs of the Bell Canada System, and have a reliability equivalent to that of existing high quality toll cables.

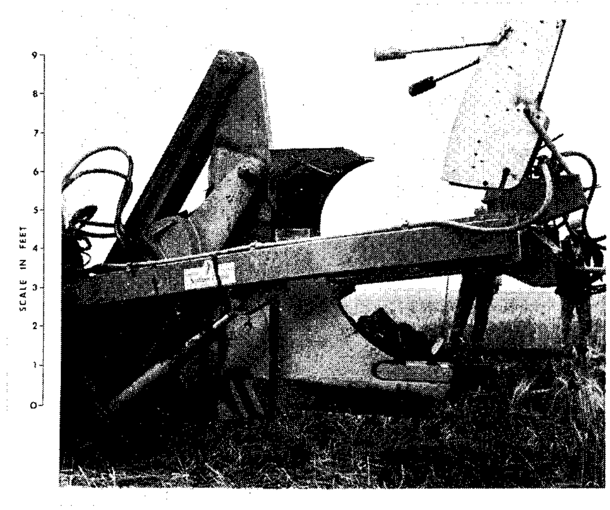


FIG. 4 PLOW SHARE

THE PCM SYSTEM

The PCM System, to which this coaxial cable will connect, will have a bit rate of 272 M bauds, will utilize a bipolar pair substitution code, and will be designated LD-4. The transmitted signal will have a rise time equivalent to a raised cosine pulse of amplitude 3.3 volts and a width of 1.7 nano-seconds at the half maximum height. The spectrum of the signal is significant in the frequency domain from 2 MHz to 490 MHz, See Fig. 5. By the time each bit of information traverses a complete repeater section, that signal will be acting upon and conversely it will be acted upon, by at least 100 other signals due to a combination of attenuation and phase delay effects. While amplitude and phase equalization prior to the regenerative section of the repeater will reduce such pulse dispersion, each bit of information will still cover slightly more than two time slots prior to entering the regenerator of the repeater.

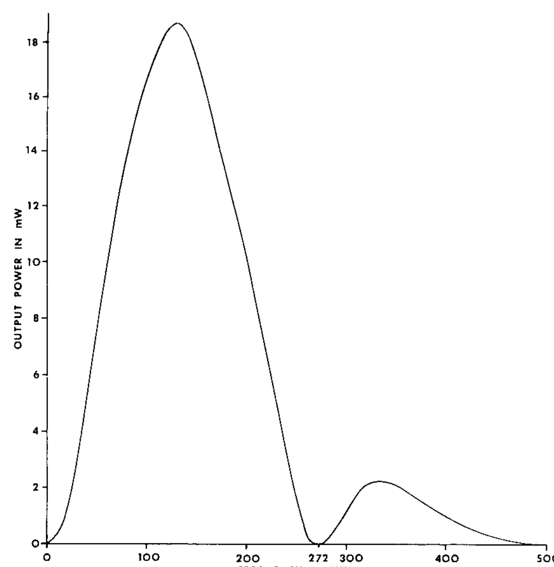


FIG. 5 OUTPUT POWER SPECTRUM OF PULSE TRAIN

The requirements for a coaxial unit to be used on a digital system are, in most respects, not as severe as those for an analogue system. The digital system does, however, have a few additional problems. Since its wide frequency spectrum includes some very high frequency components, which are reflected at impedance perturbations normally insignificant in the lower frequency analogue system, local changes in the characteristic impedance must be controlled to minimize error. Any impedance discontinuity will reduce the information-bearing signal by an amount proportional to the signal reflected. This

reflection is subsequently rereflected from the sending repeater to interfere with subsequent pulses. These effects are both magnitude and phase sensitive and if not controlled can be a serious source of intersymbol interference. Initially this condition will be controlled by tight attenuation ripple requirements,T.D.R. measurements and wide frequency spectrum SRL requirements. Eventually high frequency techniques such as, high voltage reflectometry or frequency modulated continuous wave radar fault location will have to be developed.

System studies of initial traffic density, growth, equipment and cable costs, operating costs, etc., indicated that system costs had a relatively flat optimum with respect to coaxial unit size. Consequently, the standard .375" size was selected, and standardized in a 12-unit cable makeup.

It remained therefore to reduce the cost of the coaxial unit consistent with its electrical characteristics. These were set, for the digital system, at ± 1% of the attenuation of the existing serrated seam .375" unit from 1 to 320 MHz, with a nominal characteristic impedance at 2 MHz of 75 ohms in the finished cable. For analogue carrier systems, the frequency spectrum over which the electrical characteristics were to be rigidly controlled was 500 kHz to 64 MHz. For CATV systems control was extended up to 300 MHz.

THE CABLE

The cable for the LD-4 system will employ corrugated support members in both the coaxial unit and the sheath. By this means the effect of any change in dimension, that can occur during and after installation will be minimized, and the electrical characteristics of the installed cable improved.

The cable was developed by adopting established techniques where this was economically advantageous. New developments were restricted to those areas where the effort expended would contribute to achievement of optimum results.

The Coaxial Unit

Physical. Various .375" coaxial unit constructions were considered for this application and evaluated relative to the physical characteristics of the existing serrated seam design. The crush resistance, and the change in impedance which occurs when a semi-air dielectric coaxial unit is bent, were given particular attention. Both effects are considered more critical to higher frequency systems.

In addition to the normal installation forces that will be encountered by the new coaxial unit in regular service it will also be used in stub cable, where a unit radius of bend of less than 6" will be required. The same coaxial units were considered necessary in the stub cables to minimize any impedance mismatch between cables adjacent to the repeater.

Tests on various .375" units with flat outer conductors, indicated they had inferior handling characteristics relative to the corrugated designs. The X-ray photographs below (Fig. 6) show the effect of a typical bend on the internal dimensions of the serrated seam unit and a unit with a solid corrugated outer conductor.

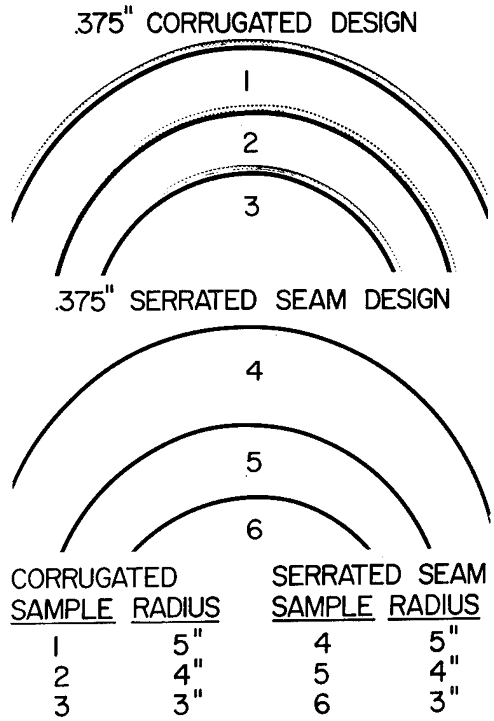


FIG. 6 *EFFECT OF BEND ON INTERNAL DIMENSIONS*

The difference in crush resistance between flat and corrugated designs can be seen in Fig. 7.

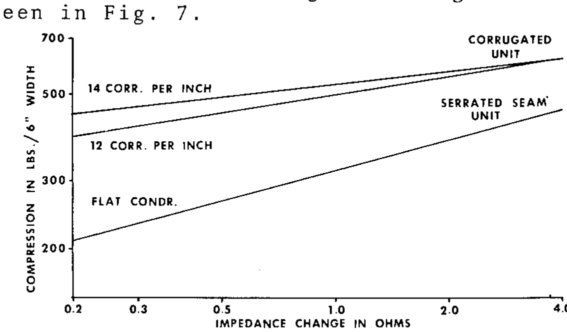


FIG. 7 *AVERAGE IMPEDANCE CHANGE UNDER COMPRESSIVE FORCE*

TABLE II

MANDREL 6" RADIUS	SERRATED SEAM DESIGN BENT	SERRATED SEAM DESIGN STRAIGHT	CORRUGATED DESIGN BENT	CORRUGATED DESIGN STRAIGHT
	OHMS		OHMS	
After 1st Bend	.32 to .90	0 to .36	0 to .23	0 *
" 2nd "	.46 to 1.12	.23 to .76	.17 to .21	0
" 3rd "	.52 to 2.28	.30 to .79	.23 to .38	0
" 4th "	.88 to 2.59	.28 to .93	.23 to .34	0
" 5th "	1.91 to 3.95	.52 to 1.12	.30 to .52	0 to .23

* 0 *implies a value below level of detectability.*

Table II results are representative of the change in impedance which can occur in the .375" serrated seam and the corrugated designs, when the unit is bent and when the unit is subsequently straightened.

Economics. Of the four materials used in the .375" serrated seam design, the conductors account for approximately 80% of the material cost of the unit. Two approaches were investigated; (i) the use of a thinner outer copper conductor to take advantage of skin effect and (ii) the use of aluminum. It was recognized in (i) that a laminate of the conducting member and a supporting member, such as steel, would be required. This cost was included in the evaluation.

Various methods were investigated to achieve a suitable laminate. These included metallurgical bonding, soldering, thermoset, epoxy and thermoplastic bonding. The final selection was made on the bases of economics, consistency of bond, ease of processing, etc., and was essentially the method described by W.G. Nutt[3] et al at the Seventeenth Symposium, 1968. A square edged laminate was selected to take advantage of laminates in wider widths, and to permit a circular outer conductor configuration with a butting type joint.

Table III shows the effect of tape thickness on the attenuation of a 0.375" coaxial unit at various frequencies. Note that at 1 MHz and 600 kHz there is an optimum at .004" and .005" respectively.

Normal variations in tape thickness about the nominal were found to alter the attenuation at 500 kHz by approximately 2%, if 0.0035" material was used, and 1% if 0.0045" material was used. Above 1 MHz the effect was negligible and of little practical significance over the equalizing section of the analogue system considered.

Neither the characteristic impedance or the phase constant were found to alter significantly with normal tape thickness variations, on tapes with nominal dimensions between 0.003" and 0.005".

The temperature coefficient of attenuation varied with tape thickness as shown in Fig. 8.

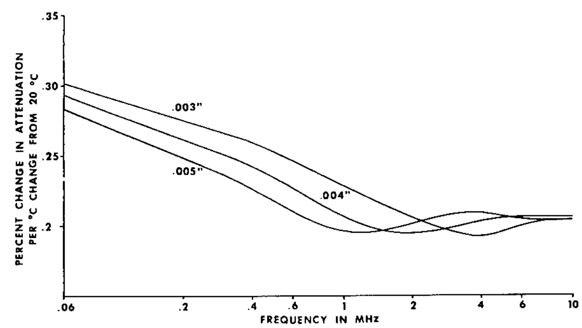


FIG. 8 EFFECT OF TAPE THICKNESS ON TEMPERATURE COEFFICIENT OF ATTENUATION

TABLE III

OUTER CONDUCTOR THICKNESS IN INCHES	ATTENUATION dB/1000' AT 68°F kHz 60	200	400	600	MHz 1	4	10	100
.002	.3529	.4722	.5795	.6620	.7947	1.445	2.320	7.380
.003	.2839	.4018	.5103	.5956	.7368	1.463	2.325	7.371
.0035	.2641	.3820	.4918	.5793	.7266	1.469	2.323	7.367
.004	.2493	.3674	.4790	.5692	.7231	1.470	2.322	7.363
.0045	.2378	.3564	.4701	.5635	.7236	1.469	2.320	7.358
.005	.2286	.3479	.4642	.5609	.7259	1.468	2.319	7.354
.006	.2149	.3363	.4586	.5612	.7311	1.466	2.316	7.346

Fig. 9 shows relative cable attenuation-cost figures, in dollars per the reciprical of attenuation, or "dB·dollars", versus the coaxial unit tape thickness. From this figure it can be observed what the attenuation of the cable would be, relative to a specific tape thickness and a fixed dollar cost. Namely, with

.005"	.004"	.003"	tape,the losses would be
65dB	65dB	67dB	for $x at 400kHz
78dB	77dB	78dB	for $x at 600kHz etc. or

conversely, the cost of the cable for the same attenuation would be -
$65 $65 $67 at 400kHz etc.

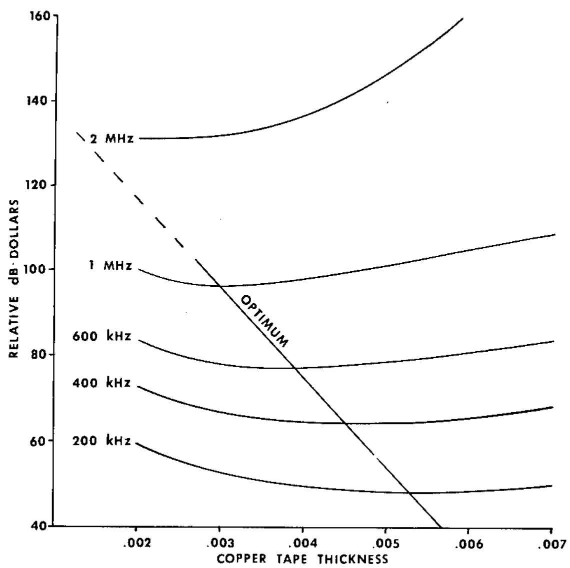


FIG. 9 RELATIVE ATTENUATION-COST FACTOR AS RELATED TO OUTER CONDUCTOR TAPE THICKNESS IN INCHES

The substitution of aluminum to replace copper as the outer conductor, was found to increase the attenuation of the unit by approximately 6%. This would have affected system optimization and reliability figures. To maintain the same attenuation in the unit, it was necessary to increase the diameter of the unit by 5%, with an overall cable saving of less than 4%. These savings would have been offset by possible splice problems and increased costs associated with the use of larger diameter cables, such as shorter lengths, increased testing and splicing, duct and manhole space allocation etc., and were not considered justified

The result of the economic analysis was that a .004" thick copper tape was selected on the basis of its effect on overall cable cost, attenuation and the anticipated minimum frequency of operation.

The substitution of aluminum for copper in the centre conductor was found to be uneconomical. The saving that could have been realized by the reduced cost of a copper-clad aluminum centre conductor was offset by the cost and difficulty of obtaining additional power feeding locations, particularly in remote areas. Copper centre conductors will continue to be used until a significant differential exists between these two costs.

Electrical. The use of a corrugated outer conductor of 0.004" copper, laminated to steel, brought into play a number of interrelated electrical, physical and economic factors which depended on the shape, depth and number of corrugations per inch selected. To simplify this work a computer program was developed to evaluate quickly their effect on the electrical characteristics of the unit.

COMPUTER PROGRAMME

The computer programme was used to obtain, within certain dimensional restrictions, the best outer conductor shape consistent with attenuation and impedance requirements and physical deformation. More than fifty designs were evaluated from which the nominal twelve-per-inch corrugation design was chosen to provide the optimum combination of physical and electrical characteristics.

The programme calculated the primary parameters, and applied them to the long line equations shown below.

The attenuation constant α, the phase constant β, and the characteristic impedance $|Zo|$, were obtained over a frequency spectrum ranging from 10 kHz to 500 MHz.

$$\alpha = \left[\frac{1}{2}\left\{[(R^2+\omega^2L^2)(G^2+\omega^2C^2)]^{\frac{1}{2}}+(RG-\omega^2LC)\right\}\right]^{\frac{1}{2}}$$
NEPERS/UNIT LENGTH .... (1)

$$\beta = \left[\frac{1}{2}\left\{[(R^2+\omega^2L^2)(G^2+\omega^2C^2)]^{\frac{1}{2}}-(RG-\omega^2LC)\right\}\right]^{\frac{1}{2}}$$
RADIANS/UNIT LENGTH .... (2)

$$|Zo| = \left[\frac{R^2+\omega^2L^2}{G^2+\omega^2C^2}\right]^{\frac{1}{4}} \Omega \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The first step towards calculation of the primary parameters required that an effective inner diameter for the outer conductor be obtained, and the electrical requirement of a nominal 75 Ω characteristic impedance at 2 MHz was used as the criterion. Since the high frequency impedance may be regarded as mainly capacitance dependent, the effective diameter was based on an equivalence of capacitance

between a straight coaxial unit and the corrugated design, as shown in appendix 1A. Calling this diameter D_1, the inner conductor D_2, and assuming a specific inductive capacitance of ε for the unit, the primary admittance parameters could easily be defined as shown in equations 4 and 5.

$$C = \frac{2\pi\varepsilon}{\log_e\left(\frac{D_2}{D_1}\right)} \text{ farads/meter length..... (4)}$$

$$G = 2\pi.f.C.\tan\delta \text{ Siemens/unit length .. (5)}$$

Where $\tan\delta$ is the dissipation factor, and is normally of the order of 10^{-4} for disk air type insulation.

The series parameters resistance and inductance are subject to the skin effect phenomenon which produces a complex relationship between impedance and frequency. The solution to the Bessel equation (6), describing the change in current density across a tubular conductor carrying a sinusoidal current of angular frequency ω, provides the relationship of the impedance with frequency (equation 7).

$$\frac{d^2I}{dR^2} + \frac{1}{R}.\frac{dI}{dR} - jm^2I = 0 \text{ .... (6)}$$

Where $m^2 = 4\pi\omega/\rho$ and I is the current density at distance R from the centre.

$$Z=(R+j\omega L)=X(r)\left[\frac{I_o(X_2)+\frac{I_o'(X_1)}{K_o'(X_1)}K_o(X_2)}{I_o'(X_2)+\frac{I_o'(X_1)}{K_o'(X_1)}K_o'(X_2)}\right] \text{(7)}$$

$$\text{Where } X(R) = \frac{jm\rho}{\pi D_2} \text{ ; } X_1=mD_2\sqrt{j} \text{ ; } X_2=m(D_2+t)\sqrt{j}$$

$$I_o(X\sqrt{j}) = BER_o(X)+jBEi_o(X) \text{ : Kelvin functions of first kind}$$

$$K_o(X\sqrt{j}) = KER_o(X)+jKEi_o(X) \text{ : Kelvin functions of second kind}$$

Separating equation 7 into its real and imaginary components provides expressions for the resistance and inductance parameters in terms of Kelvin functions. Their evaluation may be carried out as accurately as the limitations on calculating the Kelvin functions will allow. These functions are not easily solved by conventional means and are best determined using computer methods. The basic set of power series defining the functions add complications to the method of programming because of the large value which each term may attain, therefore asymptotic approximations to the series were used for the larger arguments. A description of the modifications to these approximations and their subsequent evaluation is contained in Appendix 1.B.

The computer programme determined the resistance and inductance for the inner and outer conductors separately, and added them, with suitable modification to the outer conductor components to reflect the excess length due to the corrugation. The inductance due to the flux within the dielectric was also taken into consideration in equation 7, as was the component due to flux produced in the outer conductor by the inner conductor.

It is interesting to note that using an IBM Series 360 Model 67 computer, a complete output was obtained using approximately 20 C.P.U. seconds at a cost of $8.00.

To confirm the accuracy of the programme a series of tests were made on conventional coaxial designs before application to the present corrugated design. Given the configuration, it was found the electrical parameters could be predicted to a 99% accuracy (cf. the comparisons in the Results section).

Coaxial units with the desired electrical characteristics were then manufactured and evaluated with 14, 12 and 10 corrugations per inch and depths of corrugation of .034" and .037". The following observations were made.

Units with 14 corrugations per inch were found to form well and have good impedance control under compression and when bent, see Fig. 7 and 10. Their attenuation was higher than predicted by the computer programme at the lower frequencies. This was traced to deformation of the outer copper conductor in the valley of the corrugation, and resulted from the force necessary to corrugate the copper-steel laminate.

12 corrugations per inch, with corrugation depths between .034" and .037",were found to form well, and have good impedance control under compression and bend. They also met the predicted electrical characteristics.

10 corrugations per inch had similar characteristics to the 12 corrugation per inch design except that the impedance spread in the .034" design was greater when the unit was bent.

The unit selected has approximately 12 corrugations per inch to obtain the best compromise between electrical and physical characteristics, manufacturing convenience and cost. Fig. 11 is a photograph of the final unit design.

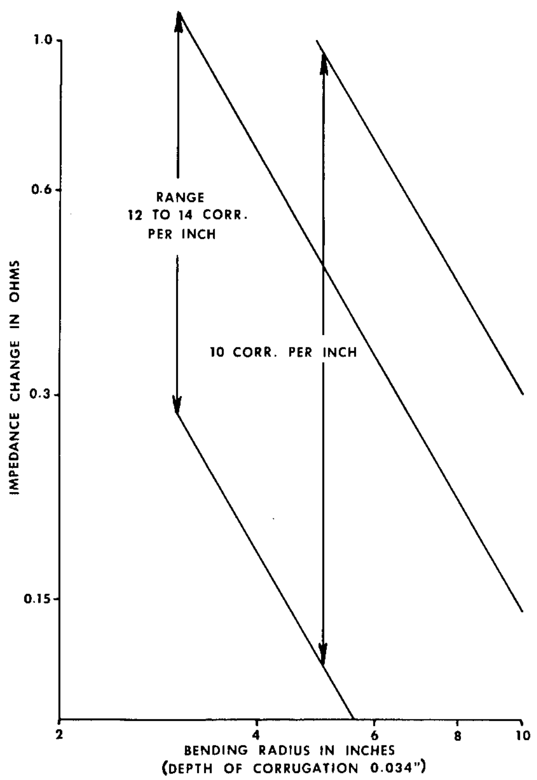


FIG. 10 CHANGE IN IMPEDANCE VERSUS BENDING RADIUS

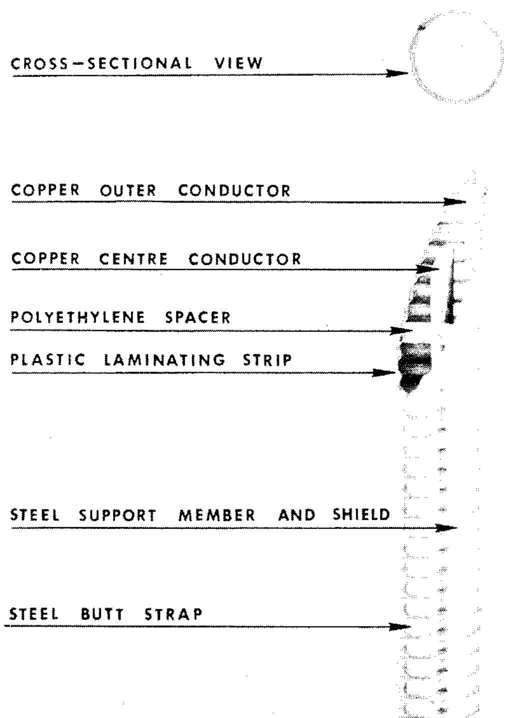


FIG. 11 THE NELC-375 COAXIAL UNIT

Raw Material. As with any new product comprising a number of individual components, the problem of raw material selection, procurement and control was a major factor in this development. Some of these problems which may be of general interest are presented here.

The material that was found to be the most critical in the control of impedance and structural return loss was the steel outer conductor support member. Using standard commercial material the nominal thickness on some tapes was found to vary from the nominal specification thickness by as much as 10%. Roll camber and end effects added to the problem, as did cyclical variations about the actual nominal.

An X-ray device was obtained to continually monitor thickness variations. This confirmed thickness variations predicted by S.R.L. measurements. Fig. 12 shows a theoretical relationship[4] between tape thickness and S.R.L. levels, assuming a pure cyclical variation in the tape thickness. The degree of correlation in the results varied with the degree of randomization in the cyclical pattern of the steel tape thickness variation. Also, since the tapes with the worst variations were obtained during early line development, other random effects were occurring. The effect of an automatic feedback controlling thickness in one supplier's plant was observed just above 10 MHz, while the effect of mill rolls in other suppliers' material was observed around 80 and 140 MHz.

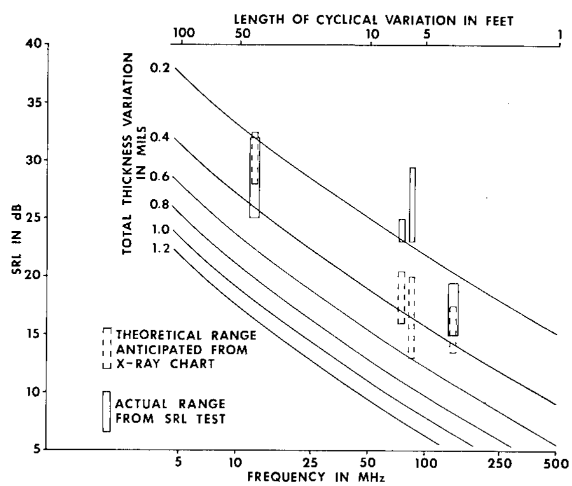


FIG. 12 CYCLICAL VARIATION IN TAPE THICKNESS VERSUS SRL

The steel tape supplier finally selected is now obliged to remove a specified percentage at each end and off each side of the tape roll. The tape is then

processed further in the cable plant for selection and removal of any additional irregularities. This procedure permits the economic use of commercial material with a practical scrap allowance.

The selection and analysis of the best type of solder presented a number of problems, some of which are still under evaluation.

An "aging" phenomena was found to be critical to the rolling operation performed on the solder wire prior to soldering. This was finally related to the length of time which elapsed between the solder wire manufacturing and rolling operations, and was resolved by limiting this time period to 3 months.

Creep in the solder seam has to be limited to acceptable levels over the life of the cable by the use of a special solder and/or by the elimination of stress in the joint. The addition of certain elements to the solder reduces the rate of creep, but they also decrease the solders wetting properties and increase its plasticity range. These two factors can in turn make manufacture and impedance control more difficult.

Stresses imparted to the seam prior to and after forming of the outer conductor have to be controlled. Long term studies are continuing on creep and until these are completed it is recommended that very short radius bends, in the order of 3", be encapsulated in a rigid epoxy as a precautionary measure.

While low temperatures are normally an asset in retarding the aging mechanisms associated with cable materials, the effects of tin plague are not observed until temperatures are below 0°C. Although the consensus of opinion was that the probability of tin plague was extremely remote, it was decided the risk was not justified and small trace elements of antimony and bismuth were added to the solder.

The Cable Sheath. A number of factors ranging from manufacturing to installation, and cost to reliability, were involved in the selection of the sheath.

The laboratory/field trial, reported in the introduction to this paper, was part of an overall program designed to obtain a sheath more suited to this application and indirectly a replacement for lead.

Our objection to the use of lead was its high cost and weight, and the limited mechanical protection it afforded the underlying coaxial core. There was also a desire to supply longer lengths of cable, and to reduce the number of splices, testing and impedance matching points.

A relatively new sheath, which resulted from a development in Germany and was reported[5] by Dr. K. Andreson and D.R. Stein at the 11th Symposium, showed considerable promise in the initial physical and electrical evaluation. It was subsequently determined that this sheath could be produced and installed with a considerable saving over lead, and with less detrimental effect on the electrical characteristics of the coaxials. What remained therefore were questions as to its in-service and reliability characteristics.

Field Experience. While laboratory work and theoretical studies are invaluable in assessing the performance of a product, field experience is the best criterion on which to rely. In the case of a new product such experience is never available and extensive field trials are usually necessary.

In evaluating the corrugated steel sheath, it was fortunate that excellent field records were available for a similar product covering a 10-year period in Germany. In addition, this data could be compared directly with similar data on a lead sheathed armoured cable in the same environment.

Although it is difficult and in some cases impossible to compare fault statistics from one country to another, due to different environmental conditions etc., an analysis of two designs in the same environment can give a good appreciation of their relative performance in an other area.

Table IV is a summary of information obtained originally from the German telephone system for the year 1967 and recently updated to 1969. This information was supplied through the courtesy of the German Post Office.

TABLE IV

FAULT RATE PER 100 MILES OF CABLE DURING 1969

TYPE OF DAMAGE	LEAD & ARMOURED	CORRUGATED STEEL
MECHANICAL	6.2	6.2
LIGHTNING	0.4	1.0
SPLICES	1.5	1.8
OTHERS	4.4	2.0
	12.5	11.0

Note 1: *This covers 60,000 miles of medium and long distance toll cable, 90% of which is directly buried at a depth of 30 to 40 inches and protected by tiles.*

Note 2: *By 1969 22.3% of the installed system was corrugated steel against 17.9% in 1965. 80 to 85% of newly installed long distance toll cables will be of this design in 1971 and 95% in 1972.*

Two significant points to observe in the above comparison is the higher incidence of lightning trouble in the steel sheath and the lower "other" problems. The former has resulted in the German Post Office deciding, as of 1971, to install a shield wire directly over the corrugated steel sheathed cable. This will reduce the incidence and magnitude of strikes entering the cable and significantly reduce the fault rate due to lightning. The "other" category covers earth displacement, vibration, rock movement, electrolytic and chemical corrosion.

Unfortunately,comparable data was not available within the Bell Canada System. The best estimate obtained was that the incidence of trouble was in the order of 3 per 100 miles,with approximately 60 percent of the damage reported being mechanical.

A value of 0.4 service interruptions per 100 miles per year has been suggested for the PCM system, however, a value of 1 appears more practical without going to the full extent of a "hardened" system.

Sheath Design. In view of the high reliability that is desired from the cable, and the length of time which may elapse between an alarm and repair crews taking corrective action, a modification has been made to the basic corrugated steel sheath.

An aluminum tape has been bonded to the inner surface of a polyethylene jacket containing longitudinal flutes to increase the dimensions of the outer envelope and reduce its pneumatic resistance.

In the field the cable will have two independent gas pressurization systems. The inner system being static at approximately 12 psi and the outer dynamic from 11 to 6 psi.

The aluminum tape will be electrically bonded to the outer steel envelope at all repeater locations,to assist in reducing the sheath potential during a lightning strike and improve the reduction or shielding factor of the steel sheath. Fig. 14 compares the reduction factor of the proposed design to a Lepeth PJ construction with an identical core.

Fig. 13 is a photograph of the complete cable.

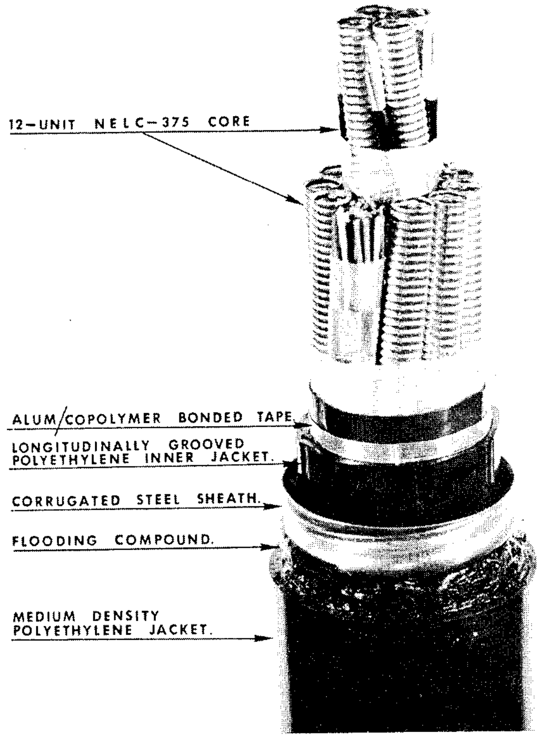
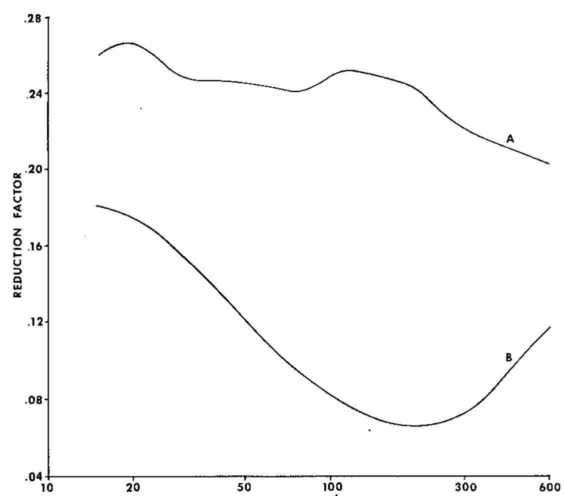


FIG. 13 COMPOSITE LD-4 CABLE



(A) LD-4 Cable with Lepeth PJ Sheath.
(B) LD-4 Cable with Aluminum & Corrugated Steel Sheath.

FIG. 14 REDUCTION FACTOR TO THE CENTRE CONDUCTOR OF A COAXIAL UNIT

Table V shows the relative material costs of the modified corrugated steel sheath against the equivalent Lepeth PJ and ARPASP sheath designs over the same core.

TABLE V

ARPASP	90%
Modified Steel	100%
Lepeth PJ	210%

The possibility remains in the design of the sheath of converting to another material should engineering requirements justify the increased cost.

Installation Procedures. While good construction practices can reduce mechanical damage, they cannot eliminate it. The integrity of the polyethylene jacket/polybutene base sealing compound will be evaluated after installation by a 20 kV DC test between the sheath and ground.

The cable will be buried at a depth of 4 ft. to reduce the incidence of mechanical damage. Within or near built-up areas, that cannot be avoided, the cable will be installed in ducts.

After installation, damage to the corrosion protection is still possible due to lightning, rodents or man. To detect this it is planned to use electrolysis test points at repeater locations where stray currents and sheath protection change. The outer envelope gas alarm system will give secondary protection.

Emphasis is being placed on the training of personnel to reduce splicing problems. In addition, the number of splices will be kept to a minimum by the use of extra-long lengths of cable.

Twin shield wires will be installed approximately 2' above the cable with 18" spacing to reduce lightning problems. By this means and the improved crush resistance of the sheath and core, crush damage due to lightning should be practically eliminated. Small pinholes caused by lightning will most likely only result in corrosion where stray currents exist[6].

MANUFACTURE

Units

Introduction. Substitution of a corrugated copper-steel laminated outer conductor for flat copper resulted in a more economic design. A metallurgically bonded seam was indicated desirable in order to obtain superior mechanical properties from the coaxial unit. A structurally self-sufficient construction, by which is meant a construction which would provide better resistance to flexing, crushing and torsional stresses on the units, without the use of other supporting components such as binders, wrappings, extruded jackets etc., could be obtained only by mechanically or metallurgically bonding the edges of the outer conductor seam. Soldering was selected because of the problems imposed by the corrugated profile, speed of manufacture and possible heat damage to the insulating discs.

To obtain a soldered seam and at the same time a smooth circular inside profile was a challenging problem which was solved by the "Butt Strap" construction. This design has many manufacturing conveniences: 1) the tooling for the corrugators is simple, 2) introduction of the solder to the joint is relatively easy, 3) the tooling for roll-forming the outer conductor is straightforward and 4) the butted construction permits the laminating of copper and steel tapes in wide widths. The "Butt Strap" did, however, introduce some new problems, such as precorrugating two separate strips, putting them together so that the two profiles nest properly, and holding them together during heating and cooling cycles of soldering. Much of the development effort was devoted to solving these problems.

Considerable work was also put into the development of the laminating equipment, the Disc Applicator for fast and efficient application of discs on the centre wire, forming the outer conductor into a circular tube, rolling the solder wire into a ribbon and soldering the seam. A brief description of some of the problems we faced and the present equipment is given in the following paragraphs.

Simplicity and reliability of operation were always the guiding principles in the design and development of this facility. It was found convenient to separate the laminating and coaxial manufacturing operations. This provides some versatility in production. The volume of production foreseen, and the advantages of low initial cost, made a coil to coil type of manufacturing schedule the most attractive system, instead of a continuous running mill.

Laminating. Laminating copper to steel using an adhesive copolymer film is an apparently simple process, but practical utilization of this process introduces many manufacturing problems[7]. These are 1) cleanliness of the bonding surfaces, 2) providing adequate heat transfer to obtain laminating temperatures, 3) registering the edges of the three components, 4) contacting the bonding faces and 5) thickness control.

The copper and steel tapes are scrubbed, degreased, rinsed and dried in a specially designed degreaser which uses trichloroethylene as the solvent.

The principle of electrical resistance heating has been used in the Laminator illustrated in Photograph A. Transferring an adequate quantity of heat into the tapes by contact type heaters proved to be slow and inefficient. Excessive surface temperatures in the copper could give rise to tarnishing and oxidizing. The resistance heating arrangement has worked very well.

Tracking and alignment of the edges of the tapes are serious problems, especially on thin and delicate materials such as the 0.004 in. thick copper tape. We have overcome many of these problems by employing floating type guides.

When hot, the copolymer ribbon becomes sticky and adheres to any hot object it contacts. Further, when a small quantity of this substance is deposited on a roller, over which the hot laminated tape passes, the resulting hot copolymer lump picks up more of the same, thus accumulating large quantities in a short time. Consequently, we have avoided contacting any hot rolling surfaces with the laminated tape.

The final thickness is obtained by squeezing the semi-bonded tapes between a pair of cool rollers.

The Laminating line has operated satisfactorily at speeds up to 120 feet per minute. Peel strengths usually obtained are in the neighborhood of 16 to 18 lbs/in.

Insulating. Application of Polyethylene discs on the center wire at high speeds has undergone much development. On conventional machines there are two distinct problems: 1) orienting and feeding the discs at the required rate and 2) slitting and applying discs on the centre wire. The equipment available for orienting and feeding were found to be too slow for the line speeds contemplated for this unit.

Considerable effort was spent in developing a fast feeder for loose discs which could deliver the discs in excess of 2000 per minute. However, the oriented discs still had to negotiate the feeding tracks on their way to the disc applicator and many small, but significant, factors contributed to the frequent stoppage of disc flow, such as static electricity, foreign particles and plastic dust, to name only a few.

After numerous trials mechanical force feeding of the discs was found to be the answer and the idea of a disc chain evolved. Instead of punching loose discs from a plastic strip, a chain of discs is stamped. This chain is synchronously fed into the disc applicator by a pair of squeeze rollers. The disc applicator wheel has cutting knife elements mounted on it which sever the disc from the chain The rest of the disc application mechanism is similar to that on the serrated seam machines; namely, the slitting of the discs radially, opening the slit by passing the slit disc over a gradually expanding guide member and depositing it on the centre wire. Photographs B and C illustrate this machine.

This system has performed very well. Speeds up to 120 fpm can be obtained and the frequency of missing discs has been reduced by a couple of orders of magnitude from the existing design.

Corrugating and Tube Forming. The butt strap construction requires two corrugators, one for the laminated tape and the other for the butt strap. The profile of corrugation of the butt strap is designed so that proper nesting is obtained when the butt strap is laid over the corrugations of the laminated tape. The drive for the two corrugators is arranged so that an identical number of corrugations are produced on each tape per each revolution of the corrugator drive shaft.

The Tube Former is a simple roll forming machine with eight roll stands. All the eight sets of rolls are driven and the tooling is designed so that the insulated centre conductor passes right through the tooling.

Photographs D and E illustrate the Corrugator and Tube Former respectively.

Solder Flattening and Fluxing. This equipment required considerable development. The starting material is a solid solder wire. When a soft solder wire is rolled into a ribbon, the width obtained is dependent upon many variables such as the surface roughness of the rolls, the temperature of the rolls, the lubrication of the rolls, the front tension of the ribbon, the back tension of the incoming wire, etc. All these variables have to be held within very narrow limits in order to obtain accuracy of dimensions of the ribbon. Solid solder wire is rolled and the solder ribbon thus produced is then passed through a Flux Applicator to produce a thin covering of flux on the ribbon. In this manner the flux remains on the outside of the ribbon where it is most effective.

Soldering Apparatus. The combination of the tube formed by the laminated corrugated tape, the fluxed solder and the butt strap are heated to soldering temperature by means of a radio frequency induction coil. The power generation equipment is simple and conventional.

The joining elements are held together by a fixture during their heating and cooling cycle[8].

A drum capstan and a traversing take-up form the rest of the apparatus.

Performance. The insulating and soldering line can run at line speeds up to 120 fpm. The present operating speed of the line is 80 fpm. The drive arrangement and the control of the line are quite simple.

Cable

General. Special equipment, atmosphere control equipment and a complete reorganization of the production facilities were necessary to manufacture the LD-4 cable. The entire unit manufacturing area will be temperature, humidity and dust controlled.. The cabling, jacketing, sheath welding and stripper-locate areas will be completely air conditioned. The jacketing line, the stripper-locate equipment and the inspection facilities have also been specially modified to suit the needs of manufacturing. A brief description of some of the new facilities is presented in the following paragraphs.

Cabling Facilities. Cabling of the coaxial units may introduce Structural Return Loss particularly at lay frequencies. Experience with this problem has been applied to the development of a new Cabler designed especially for coaxial cables. This equipment will be installed in 1972. It will have twelve coaxial give-ups in the beginning with features that could extend this number to eighteen at a later time. The give-ups are located symmetrically in one plane with special consideration given to small angles of deflection at guides and lay plates. Centrifugal tensions and the cyclical variations of these will be kept to a minimum by employing a rotating capstan and a rotating take-up. This cabler incorporates good tension control systems for the give-ups and a random lay variation feature should this be necessary.

Welded and Corrugated Sheath Line. The steel sheath welding and corrugating line utilizes the inert gas electric arc welding process. This line has been well proven in many countries particularly in Europe. The corrugator is of the eccentric ring travelling carriage type. Photograph F shows the Tube Forming and Welding sections of this line and Photograph G shows a close-up view of the corrugator. Following the manufacture of the welded sheath a gas pressure test is carried out to ensure the integrity of the weld. Over the welded sheath a moisture barrier of a specially formulated flooding compound is applied. This completely fills the corrugations of the sheath, thereby providing a reservoir of compound to seal any defects in the outer jacket which may arise in service.

PRODUCT EVALUATION

Electrical Characteristics

The following results are from product made during a period of 12 months on prototype equipment. Since both the equipment and the product had been under development during this period, some anomalies have had to be allowed for in the results.

Impedance. The stability of the mean characteristic impedance during processing has been impressive. For example, to allow for an anticipated decrease in impedance during the various manufacturing stages, the unit was designed to have, at the initial manufacturing stage, an impedance of 75.2 ohms at 2 MHz using a 125 nano-second pulse. Due to the excellent handling characteristics of the unit no significant decrease in impedance occurred.

The new unit's average impedance is approximately .2 ohm above the existing serrated seam design at 2 MHz, and .2 ohm below 75 ohms at "infinite" frequency. No further changes are contemplated in the impedance level.

The control of the mean characteristic impedance has been very precise with this equipment. The standard deviation of the last batch of 21 reels was within .08 ohms with an average of 75.26 ohms.

Relative to the mean characteristic impedance, the deviation of the effective characteristic impedance, when measured using a radio frequency source, was poor. The main cause of this was traced to steel raw material variations, and the same corrective action was taken as in the case of SRL problems. These deviations are critical for the analogue systems.

Fig. 15 shows the variation of the characteristic impedance with frequency based on the computer predictions. Actual measured mean values using the r.f. technique were .4 to .1% higher than predicted between .5 and 10 MHz. The present range of deviations (.8%) are shown in this figure relative to the theoretical mean for graphical purposes only. Deviations as great as 1.5% have been detected.

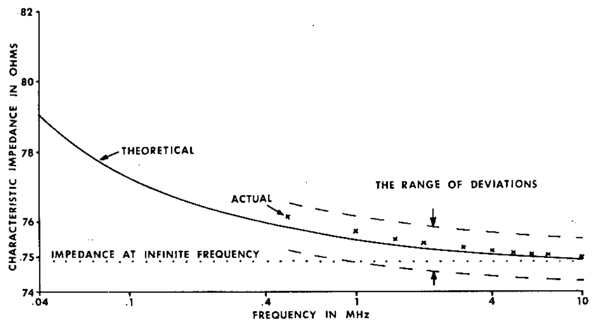


FIG. 15 *CHARACTERISTIC IMPEDANCE VARIATION WITH FREQUENCY FOR CORRUGATED .375" DESIGN*

Attenuation. The average attenuation of the coaxial unit has been found to conform to the expression $\alpha = a + b\sqrt{f} + cf$ above 3 MHz, where a=.0096, b=.729, c=.00107 and f is in MHz, for dB/1000 ft. of unit at 68°F.

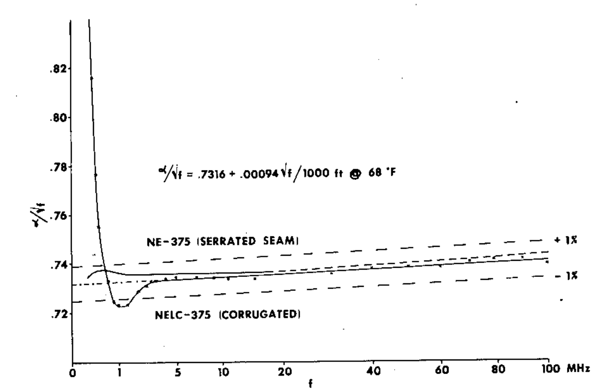


FIG. 16 *ATTENUATION DIVIDED BY SQUARE ROOT OF FREQUENCY FOR CORRUGATED AND SERRATED SEAM .375" DESIGNS*

To permit an enlarged scale for Fig. 16 the attenuation has been divided by the square root of frequency. A comparison is made with the serrated seam design, and between computed and actual measurements on the corrugated design.

The amount of ripple on the attenuation curve is very critical to the digital system and has to be controlled precisely. The maximum R.M.S. deviation desired from the mean is specified at 0.08%. Present indications are that this value is under .17% with some portion due to measurement error. More precise methods of attenuation measurement are being developed.

Phase. Fig. 17 shows the theoretical phase change predicted by the computer programme and the actual measurements made up to 12 MHz. A good correlation was obtained.

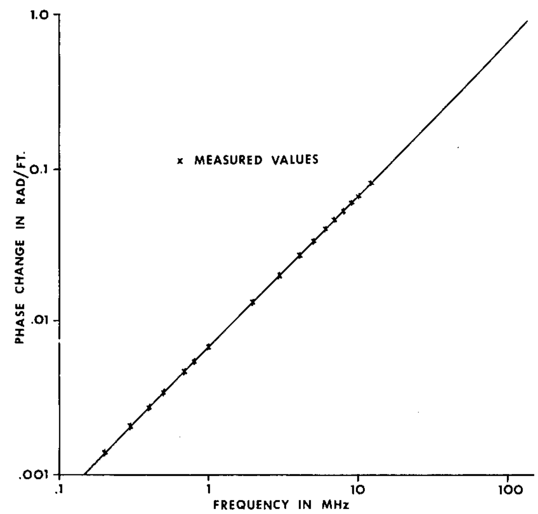


FIG. 17 *PHASE CHANGE VERSUS FREQUENCY FOR CORRUGATED .375" DESIGN*

Structural Return Loss. All units manufactured to date have been "swept", in the laboratory, from 5 to 500 MHz. Although a very high value of SRL is, in itself, unnecessary for the digital system,

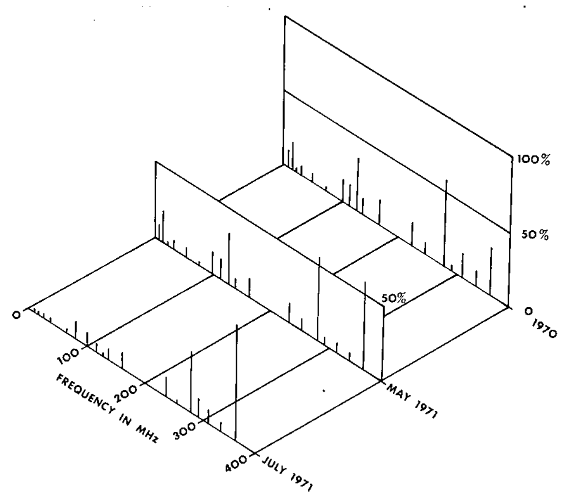


FIG. 18 *PERCENTAGE OF SRL READINGS BELOW 32 dB*

the initial object is to maintain the SRL level above 30 dB up to 320 MHz. Fig. 18 is an interesting pictorial representation of the gradual elimination of SRL problems during the development. The trouble observed in the vicinity of 350 MHz has since been removed by a machine alteration.

Subsequent processes can still alter the SRL level of the basic unit. Table VI is an example of such a problem on an early development cable, observed at the cabling lay. This trouble was detected after jacketing and was caused by a high pressure point on the jacketing line, exerting pressure on the unsheathed core.

TABLE VI

FREQ. RANGE MHz	SRL AVERAGE OF WORST VALUE IN FOUR UNITS: UNIT FORM (dB)	FINAL FORM (dB)
5 - 40	28.9	31.6
40 - 80	26.2	27.8
80 - 120	30.5	31.5
120 - 160	29.3	32.0
160 - 200	30.6	28.2
200 - 240	32.0	26.8 +
240 - 280	29.8	30.6
280 - 320	27.1	30.5
320 - 360	29.7	27.3
360 - 400	10.7	8.2
400 - 440	30.4	28.8
440 - 480	24.5	28.9
480 - 500	30.7	30.2

Crosstalk. Far end output to output crosstalk levels exceed 150 dB above 600 kHz. Fig.19 shows the results obtained between adjacent units of a 2000 ft. length of cable.

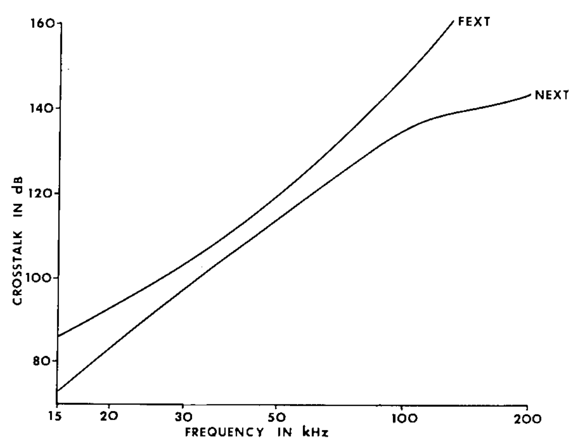


FIG. 19 NEAR-END AND FAR-END CROSSTALK BETWEEN CORRUGATED .375" UNITS IN 2000 FT. LENGTH LD-4 CABLE

Other Tests. In addition to the above requirements the unit has also to meet insulation resistance and corona requirements at 2500V DC and 2000V AC respectively, due to power feeding and power line induction limitations. Other more common tests such as dielectric strength and conductor resistance are also performed.

Physical Characteristics

The cable and the individual coaxial units have been subjected to a series of physical tests some of which have been covered in preceding sections.

Bend Tests. The complete cable has been subjected to a series of static and dynamic bend tests. Again a T.D.R. technique was used to detect any impedance change in the unit. In the static tests no impedance changes were detected until the radius of bend was less than 15". In the dynamic test, the units returned to their original impedance levels after numerous pulls around a 24" radius sheave.

Tension Tests. Pulling eyes, fitted to the end of the cable, have transferred a tension of at least 4000 lbs to the units and the sheath without any adverse effect on the electrical properties of the units.

Crush Tests. The results of Crush Tests on the complete cable are as shown in Fig. 20. It should be noted that the resistance to crush of this 12-unit cable is approximately 90% greater than the 8 unit ARPASP cable evaluated initially.

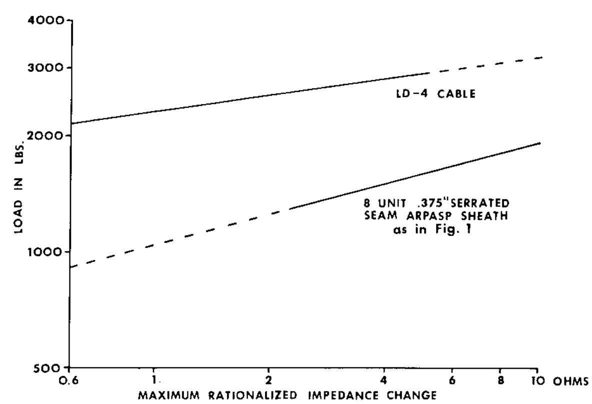


FIG. 20 THE EFFECT OF A COMPRESSIVE FORCE OVER A 6" LENGTH OF 12-UNIT CORRUGATED .375" COAX. IN LD-4 CABLE

Field Evaluation

Duct Installation. The cable, which has a nominal diameter of 2.8", was pulled into and out of a series of seven 3.5" ducts to evaluate its handling characteris-

tics. 24" sheaves were used to guide the cable in the manholes.

T.D.R. impedance traces taken before and after this series of tests indicated that the impedance changes, (a) were below 0.1 ohm over a distance that would be significant at the bit rate, (b) did not affect all units equally, and (c) were restricted to a section within 10' of the pulling eye. The maximum deviation detected was .3 ohm but well beyond the frequency spectrum of the PCM system.

The tensions necessary during the test were greater than those calculated theoretically, due presumably to the greater rigidity in the sheath and the lack of precise profile data on all duct runs used. An "apparent" coefficient of friction of 0.85 will be used for existing duct structures until more data is accumulated.

The cable was found to have sufficient flexibility for normal racking and storage in manholes.

Buried Installation. The plowshare, shown in Fig. 4, was modified to take larger diameter cable and used in a series of plow manoeuvres with the LD-4 cable, on farmland in the vicinity of Edmonton, Alberta. As in the initial evaluation the minimum radius of turn was 8 feet.

A pulse echo "Reflectomat" and a T.D.R. were used to determine the impedance levels before, during and after the plowing trial. All outer units and a sample of the inner units were evaluated. No change was detected in the impedance level of any unit by either test.

The Future. Economically there is a limit to the amount of effective protection that can be applied to a cable and the associated protective measures which can be taken in the field to protect the cable. At some point a level of reliability has to be accepted in relation to other constraints within the system. An area where further improvement is needed is in reducing the time that can elapse between a catastrophic failure, where the cable is badly cut, and a return to service. With semi-air dielectric cable, delays can, in some instances, be caused by water migrating along the cable before the repair crew arrives.

A specially designed filled coaxial cable would under these circumstances reduce the time period required to effect a permanent repair. The increased cable cost has however to be equated against the number of occurrences and system savings.

In addition, before a filled coaxial cable can be used it will be necessary to ensure that (a) the flooding compound will have no deleterious effect on the long-term stability of the coaxial unit, (b) it will be possible to retain the advantages of the gas pressurization system for toll cable and (c) system economics will not be adversely affected.

One method of achieving this would be to use the dielectric spacer discs as a water block within the coaxial units and to fill the outer interstices of the cable with a suitable filling compound. In the present design the outer envelope would then perform the dual function of acting as a gas pressure warning device and a low relative humidity environment for the coaxial core.

CONCLUSION

The program which has been described has resulted in the development of cable which can (a) be manufactured and installed more economically than a comparable lead sheathed cable, (b) withstand greater mechanical forces with less electrical degradation than existing cables, and (c) lend itself to future modifications. Assuming the precautions indicated are taken in hazardous lightning areas the cable will, we feel, prove itself to have a reliability equivalent to that of a similar lead sheathed cable in the same environment, over the life span of the system.

ACKNOWLEDGEMENTS

We are indebted to the Deutsche Bundespost for the statistical data on cable reliability, the Alberta Government Telephones for their assistance in the final plowing field evaluation and Dr. H. Dwight of M.I.T. for his comments on the skin effect evaluation. We would also like to thank all our associates in the Bell Canada/Northern Electric corporate body who actively participated in this project and in the preparation of this paper. To select and name a few would be unfair to those omitted, and to name all, impractical

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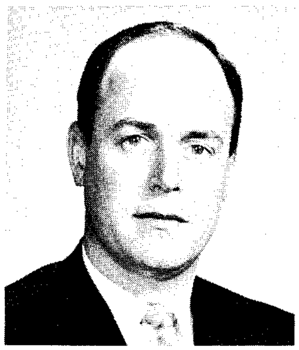


R. McClean was born in Belfast, N. Ireland, on the 11th November 1932. He attended the Belfast College of Technology to work towards Grad. Membership of the I.E.E. (U.K.), which he received in 1958. Joining the Northern Electric Co. Ltd. in 1957 as a cable design engineer in their power cable department, he was subsequently transferred to the design of communications cable in 1962. At present he is Manager, Communications Cable Development, Exploratory, in the Bell-Northern Research Cable Laboratory in Lachine, Quebec. He is a member of the Engineering Institute of Canada and the Corporation of Engineers of Quebec.

T. McManus graduated from Queen's University of Belfast in 1966 with an Honours degree in Physics. He immigrated to Canada shortly after, and began work at Northern Electric in communications cable design. He is presently a member of the Applied Mathematics Department, Cable Laboratory of Bell-Northern Research.

Dr. R.Iyengar obtained his bachelor's degree in Mechanical Engineering from Mysore University, India in 1957. He immigrated to Canada in 1960 and obtained his Master's degree in Mechanical Engineering in 1962 from Queen's University, Kingston, Ont. He joined Northern Electric Company in 1962 and returned to Queen's University in 1964 on a Northern Electric Bursary Award to complete his Ph.D which he did in 1967. He has been the Manager of the Machine Development Department of Northern Electric's Cable Division since 1967. Dr. Iyengar is a member of the Corporation of Engineers of Quebec and a senior member of the Society of Manufacturing Engineers.

APPENDIX 1.A

Considering a half cycle of the corrugation, if the profile is defined by $y = f(x)$ then the capacitance of a portion Δx at distance x, as shown in figure 1, is given by:

$$C_x = \frac{K_o \Delta x}{l_n \left(\frac{2f(x)}{D_1}\right)}$$

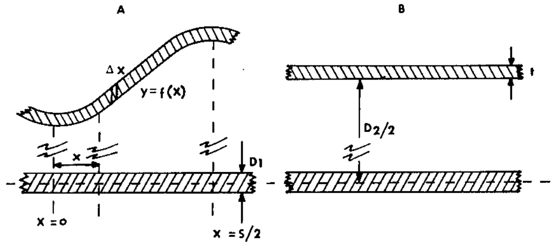


FIG. 21 TRANSFORMATION FROM CORRUGATED TO FLAT PROFILE

The total capacitance of the half cycle is obtained as $\Delta x \to 0$ by integrating from $x=o$ to $x=S/2$. The result then defines the effective diameter of the profile by equating the capacitance obtained for configuration A to that obtained for configuration B. Assuming a similar dielectric constant for both configurations, since the volume change is small, and the dielectric consists mainly of air, the effective diameter of the outer conductor may be expressed as:

$$D_2 = D_1 \; EXP \left[\frac{S}{2 \int_o^{S/2} \frac{dx}{ln(2f(x)/D_1)}}\right]$$

APPENDIX 1.B

The evaluation of the Kelvin functions was carried out using the normal power series for small argument values, and asymptotic approximations to the series for larger arguments. The approximations are "semi-divergent" in that they converge to an accurate value for the Kelvin function and then diverge quite rapidly. This stability point also varies linearly with the argument value, therefore to obtain best results the number of terms used was varied according to the size of the argument.

The first type zero order real and imaginary Kelvin functions may be approximated using:

$$BER_o(x) = \frac{e^{x/\sqrt{2}}}{\sqrt{2\pi x}} \left[L_o(x)\, COS(\theta) - M_o(x)\, SIN(\theta)\right]$$

$$BEI_o(x) = \frac{e^{x/\sqrt{2}}}{\sqrt{2\pi x}} \left[M_o(x)\, COS(\theta) - L_o(x)\, SIN(\theta)\right]$$

Where

$$\theta = \left(\frac{x}{\sqrt{2}} - \frac{\pi}{8}\right)$$

$$L_o(x) = 1 + \frac{1^2}{1!\,8x} COS\frac{\pi}{4} + \frac{1^2 . 3^2}{2!\,(8x)^2} COS^2\frac{\pi}{4} + \ldots$$

$$M_o(x) = - \frac{1^2}{1!\,8x} SIN\frac{\pi}{4} - \frac{1^2 . 3^2}{2!\,(8x)^2} SIN^2\frac{\pi}{4} - \ldots$$

Substituting the $L_o(x)$ and $M_o(x)$ expressions into the expressions describing the Kelvin functions and adding similar terms, modified expressions for the Kelvin functions are obtained which are easier to evaluate.

For example, expanding the expression for $BER_o(x)$ it may be written:

$$BER_o(x) = \frac{e^{x/\sqrt{2}}}{\sqrt{2\pi x}} \left[COS\,\theta + \frac{1^2}{1!\,8x} (COS\,\theta\, COS\frac{\pi}{4} + \frac{1^2 . 3^2}{2!\,(8x)} (COS\,\theta\, COS\frac{2\pi}{4} + SIN\,\theta\, SIN\frac{2\pi}{4}) + \ldots\right]$$

or

$$BER_o(x) = \frac{e^{x/\sqrt{2}}}{\sqrt{2\pi x}} \left[COS\,\theta + \frac{1^2}{1!\,8x} COS(\theta - \frac{\pi}{4}) + \frac{1^2 . 3^2}{2!\,(8x)} COS(\theta - \frac{2\pi}{4}) + \ldots\right]$$

$$= g_1(x) \left[COS\,\theta + \sum_{l=1}^{k} A_l \; COS(\theta - l\frac{\pi}{4})\right]$$

$$\textit{Where } A_l = \frac{(2l-1)^2!}{l!\; 8x} \; ; \quad g_1(x) = \frac{e^{x/\sqrt{2}}}{\sqrt{2\pi x}}$$

Extending this to nth order functions of all four kinds of Kelvin functions a set of expressions may be written.

$$BER_n(x) = g_1(x)\ COS\theta + \sum_{l=1}^{k} (-1)^l\ Al\ COS(\theta - l\frac{\pi}{4})$$

$$BEI_n(x) = g_1(x)\ SIN\theta + \sum_{l=1}^{k} (-1)^l\ Al\ SIN(\theta - l\frac{\pi}{4})$$

$$KER_n(x) = g_2(x)\ COS(\theta+\pi/4) + \sum_{e=1}^{k} Al\ COS(\theta+(l+1)\frac{\pi}{4})$$

$$KEI_n(x) = g_2(x)\ SIN(\theta+\frac{\pi}{4}) + \sum_{l=1}^{k} Al\ SIN(\theta+(l+1)\frac{\pi}{4})$$

Where

$$g_1(x) = \frac{e^{x/\sqrt{2}}}{\sqrt{2\pi x}}\ ; \quad g_2(x) = \sqrt{\frac{\pi}{2x}}.e^{-x/\sqrt{2}}\ ;$$

$$\theta = \frac{x}{\sqrt{2}} - \frac{\pi}{8} + \frac{n\pi}{2}\ ;\ Al = \frac{(4n^2-(2l-1)^2)!}{l!8x}$$

A plot of term values versus term numbers for various argument values revealed that a decrease in value occurs up to the point where the term number is twice the argument value, (i.e. K=2x), indicating that proceeding further decreases the accuracy of the approximation. This point was termed the stability point, and all functions were evaluated with a number of terms less than or equal to the particular stability point for that argument.

As the argument increases, the number of terms required for maximum accuracy rapidly approaches the point where their value cannot be directly computed with conventional approaches and present computer hardware. A method of accumulative multiplication was devised and employed to obtain the best results. The method ensured that, at all times, the machine operations produced results which were within the hardware range of accuracy.

If the addition portion of the expression describing $BER_0(x)$ is rewritten as follows, then the steps required to carry out the multiplications, from the last term back to the first, become obvious.

$$Call\ z = \sum_{l=1}^{k} Alfl(\theta)$$

$$z = A_1f_1(\theta) + A_2f_2(\theta) + A_3f_3(\theta) + \ldots\ etc.$$

$$But\ A_2 = A_1B_2$$

$$A_3 = A_2B_3$$

$$A_4 = A_3B_4\ etc.$$

Where

$$Bl = \frac{(2l-1)^2}{l.8x}$$

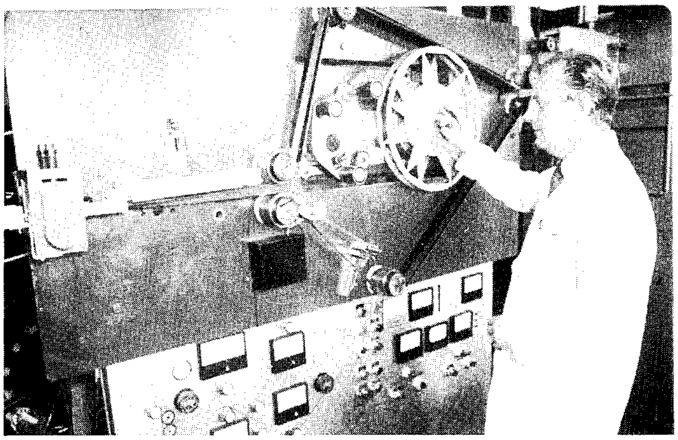
Then

$$z = A_1(f_1(\theta) + B_2(f_2(\theta) + B_3(f_3(\theta) + B_4(f_4(\theta)\ldots\ etc.\ ))))$$

then starting from the central value which is:

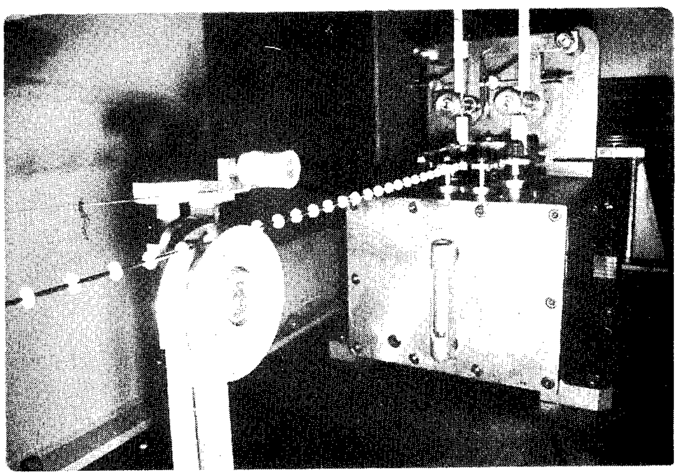
$$B_{2x}\ f_{2x}(\theta) + \left[\frac{(4x-1)}{16x^2}\ f_{2x}(\theta)\right]$$

the computations can proceed to the value of z.



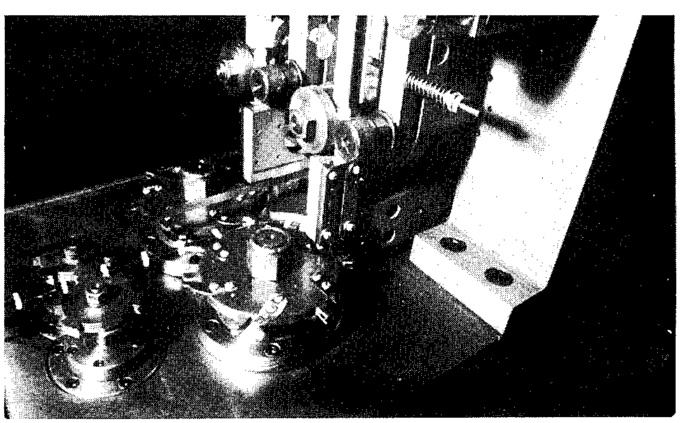
PHOTOGRAPH A

The Laminator which employs the principle of electrical resistance heating.



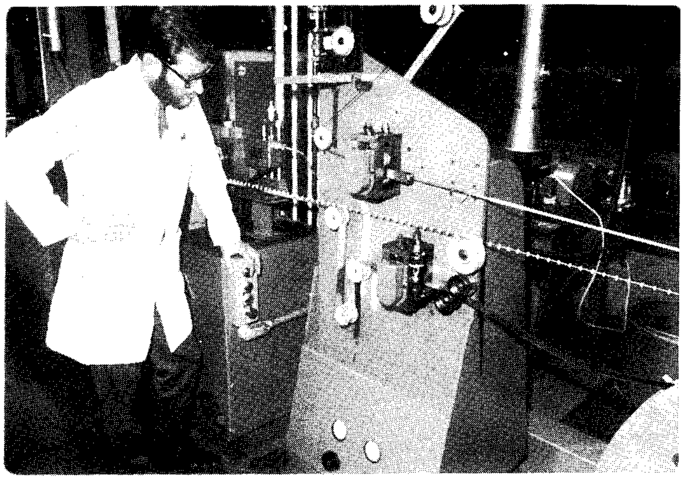
PHOTOGRAPH B

Front View of Disc Applicator.



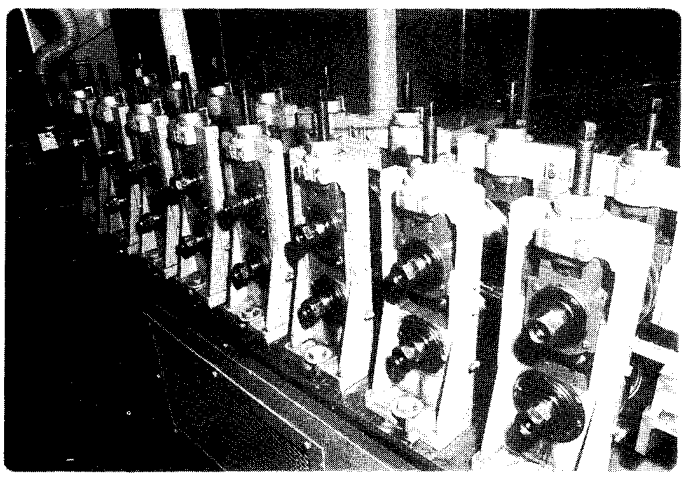
PHOTOGRAPH C

Side View of Disc Applicator.



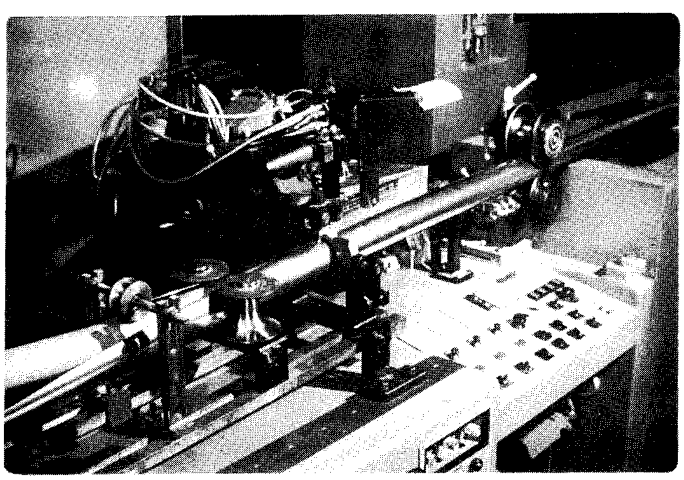
PHOTOGRAPH D

The Corrugator Complex which comprises of the corrugators for the laminated tape and the butt strap.



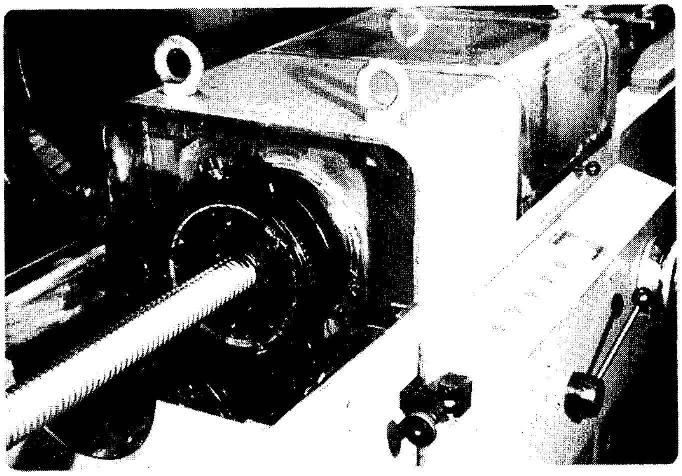
PHOTOGRAPH E

The Forming Mill for producing the outer conductor.



PHOTOGRAPH F

The Tube Forming and Welding Section of the Uniwema Sheath Welding Line.



PHOTOGRAPH G

The Welded Sheath Corrugator.

DEVELOPMENT AND PRACTICAL APPLICATION OF 375 TYPE 18 CORE COAXIAL CABLE AND ASSOCIATED ACCESSORIES

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Summary

This paper describes the development of the 375 type 18 core coaxial cable primarily for use in the 60MHz system with its electrical and mechanical characteristics, a new connector splicing method and associated splicing tools, and the test data of the cable under practical conditions.

Introduction

The demands are rapidly increasing year by year for nation-wide communication networks in Japan not only because of the expanding telephone services but also because of anticipation of various new services in the future such as video telephone, high speed facsimile, data communication and so on. In order to satisfy these demands, various new transmission systems have been extensively explored.

Table 1 shows a comparison of the typical long haul transmission line systems. It should be noted that "channel capacity per unit of a cross-section" would be the most convenient economical measure among the system parameters in Table 1. It is particularly valid for crowded regions as in the belt shaped area between Tokyo and Osaka in Japan. As shown in Table 1, the system C-60M using 375 type coaxial cable is one of the most favorable systems regarding the measure of "channel capacity per unit of the cross-section". Taking it into consideration to utilize the 3 inch conduits which are prevailing as the maximum standard size over Japan, the C-60M system using 18 core coaxial cable is expected to be one of the most effective mass transmission media. The channel capacity in this case reaches approximately 100,000 voice channels which will be on the highest level in the world at present.

Table 1 Comparison of Long Haul Transmission Systems

Item	C-60M	L-4*	PCM-100M	MM-WG
Transmission Line	375 Type Coaxial Cable	375 Type Coaxial Cable	3 Balanced Pairs Shielded	Helix Waveguide Lined Waveguide
Dimension of Line	1 core 11 mm O.D. 18 core 65 mm O.D.	1 core 11 mm O.D. 20 core 76 mm O.D.	1.2 mm ϕ PEF 3 pair unit 16mm OD	80 mm O.D. 51 mm I.D.
Frequency	Up to 61 MHz	Up to 17.5 MHz	Up to 100 MHz	40～80 GHz
Repeater Spacing	1.5 Km (0.94 Miles)	3.2 Km (2 Miles)	1.5 Km (0.94 Miles)	20～40 Km
Channel Capacity	10,800 ch Per Core	3,600 ch Per Core	1,440 ch Per Pair	300,000 ch
Channel Capacity Per Unit Cross-Section**	59	16	14***	60

* System of A. T. T.[1]

** Calculated as a unidirectional transmission.

*** Sheath diameter of one unit is supposed to be 20 mm.

This paper describes the development and practical application of the 375 type 18 core coaxial cable and associated accessories for high capacity transmission systems with the frequency region of more than 60 MHz. It was recognized that the 18 core coaxial cable should have rather better electrical characteristics than conventional coaxial cables containing less than 12 cores, in spite of the larger diameter and the more complicated structure caused by more cores. Furthermore, splicing methods, termination methods and stub cable should have been newly developed as associated accessories in order to attain complete system performance.

C-60 M System*

Figure 1. shows the long haul transmission lines of extended bandwidth developed in Europe[2] and America. The newly developed C-60 M system[2] in Japan can transmit 10,800 voice channels, 6 color television, or 30 - 36 video telephone (1MHz) channels, per pair of coaxial cores using the bandwidth of 4,287 - 61,160 KHz and transistor repeaters every 1.5km (0.94 miles) as shown in Table 2.

This system was constructed in 1970, for a route of approximate 60km (38 miles) as a field trial, and it has been studied.

* This system will be equivalent to the next step of L-4 or perhaps L-5 system in A.T.T. which is not formally published yet.

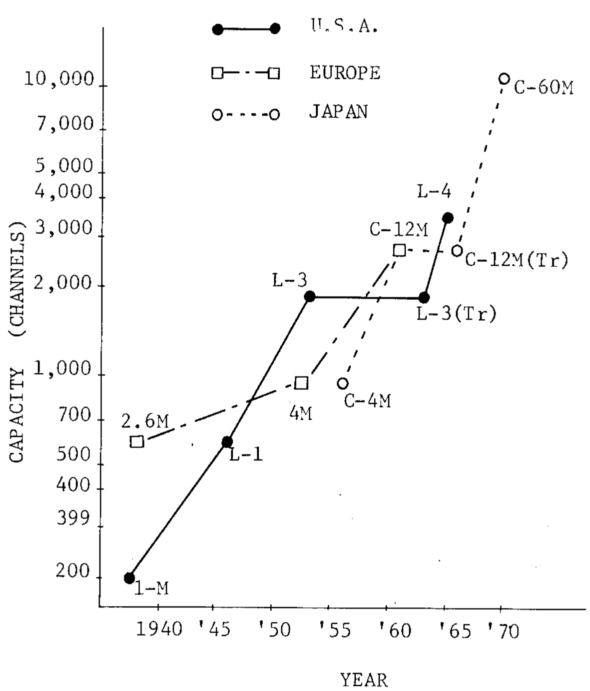


FIG. 1 DEVELOPMENT STAGES OF F.D.M. COAXIAL SYSTEMS

Table 2

Description of C - 60 M System

Channel Capacity	Telephone : 10,800 ch or Color T. V.: 6 ch
Frequency Band	4,287 - 61,160 KHz
Cable	2.6/9.5 mm (375 Type) Coaxial cable
Repeater Spacing	Standard: 1.5 Km
A G C	Common control based on Thermal A. G. C.
Power Feeding	150 mA DC maximum 1700V Constant current both-end supply (Power supply distance: 100 Km)
Supervisory	Station - Originating Oscillation method for Fault-locating. Band: 3.5 - 3.7MHz, 2KHz spacing
Hypothetical Reference Circuit	2,500Km (CH: 1 link,G&SG: 3 links,MG: 6 links,SMG: 9 links, Video: 3 links)
Noise	Telephone: 2,500 Km, 10,000 pW Terminal : 2,500 pW Line : 3 pW/km

18 Core Coaxial Cable

Structure

Cables containing up to 12 coaxial cores are available at present. Table 3 shows an evaluation of several cables containing coaxial cores greater than 14. 18 was adopted as the most suitable number of the coaxial cores considering the following conditions.

(1) The number should be even.

(2) The diameter should be less than 71.5 mm for the installation into 3 inch underground conduits.

(3) The cable structure should be electrically and mechanically stable during manufacture and installation.

The structure of 18 core coaxial cable is shown in Fig. 2 and Table 4.

It is desired that the attenuation of each core becomes as similar as possible by keeping the physical lengths of coaxial core constant, in order to facilitate the adjustment of gain of the repeater amplifier after construction and the transmission circuit alternation in case of circuit damage. The lay length ratio of the inner to the outer coaxial cores is chosen so as to keep about 1 to 2 ratio, calculated from the ratio of the average core diameters.

Because of differences in both lengths, the coaxial cores in the outer layer cross over those in the inner layer. This affects the allowable number of repeated bendings. To solve this problem, the following means were found effective by experiment.

(1) To provide paper cushion thicker than about 1 mm between both layers.

(2) To shape the outer circumference of the inner layer of the 6 cores as round as possible, by means of enough paper wrappings over the 6 interstice quads in the inner layer.

The latter is better, because the overall diameter can be kept smaller.

As for the interstice quads, it is estimated that a minimum of 20 control pairs are needed for Common Automatic Gain Control (C-AGC) circuits, outside plant alarms, express order wire, and so on. Cable structure for using a commercial test contains 36 interstice pairs (18 quads) as shown in Fig. 2.

Table 4 Nominal Dimensions of 18 Core Coaxial Cable

Outer Dia. of Cable Core (Over Wrapping Tapes)	59 mm
Thickness of Lead Sheath	2.9 mm
Outer Dia. of Finished Cable	65 mm
Weight	11.2 kg/m

Table 3 Comparison of Cables containing more than 14 cores

Number of Cores	14		16		18	20	22
Arrangement of Cores	4+10	5+9	5+11	6+11	6+12	8+12	8+14
Electrical Characteristics	○	○	○	○	○	○	○
Stability of Arrangement	○	△	○	△	○	△	○
Cable Dia. (Approximately - mm)	62	66	66	68	68	78	78
Restriction from Manufacturing	○	○	○	○	○	○	×
Restricted by Conduit	○	○	○	○	○	×	×

○ : Good. △: Not so good. × : No good.

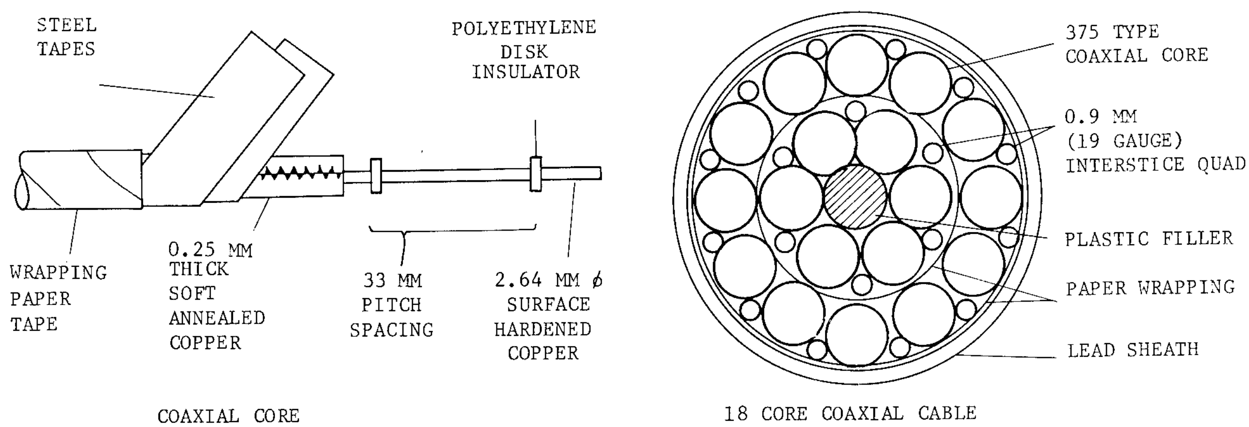


FIG. 2 STRUCTURE OF 18 CORE COAXIAL CABLE

Characteristics

Figure 3 shows attenuation constants of 18 core coaxial cables below 200 MHz. The figure includes the standard curve and the measured data on a factory length and on a 1.7 km (1.06 miles) length installed at Utsunomiya (a city north of Tokyo) described below. The difference of attenuation between both layers was too small to discriminate. The difference of physical length between two layers was measured by the resonance frequency method, and it was as small as 0.06 - 0.07%.

For the measurement of impedance uniformity for the C-60 M system, a 10 nanosecond (nS) raised-cosine pulse echo tester which has been newly developed is used. Figure 4 shows echoes of 18 core coaxial cable expressed in dB, in both cases of 10 nS pulse and 50 nS pulse. The echoes with 10 nS pulse were less by about 4 dB than those with 50 nS pulse. Cores in the inner layer are a little less than those in the outer layer. This may be caused by the effect of intersection between both layers. However, even the worst values were so good as to be 60 dB and 65 dB with the pulses of 10 nS and 50 nS, respectively.

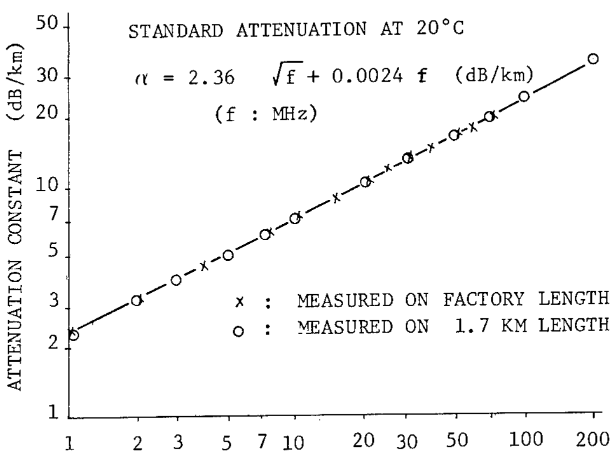


FIG. 3 ATTENUATION CONSTANT OF 18 CORE COAXIAL CABLE

Voltage Standing Wave Ratio (VSWR) below 200 MHz was measured, to investigate the periodic irregularities. Figure 5 shows an example of VSWR of the 18 core coaxial cable which displays a small spike over 100 MHz, and a very flat level as low as 1.01 - 1.02 below 100 MHz. The VSWR spike is considered to be caused by the periodic deformation during cabling process. Although the frequency is well above C-60 M system band, the irregularities are being corrected, preparing for the higher frequency systems such as C-200 M or PCM-800 M.

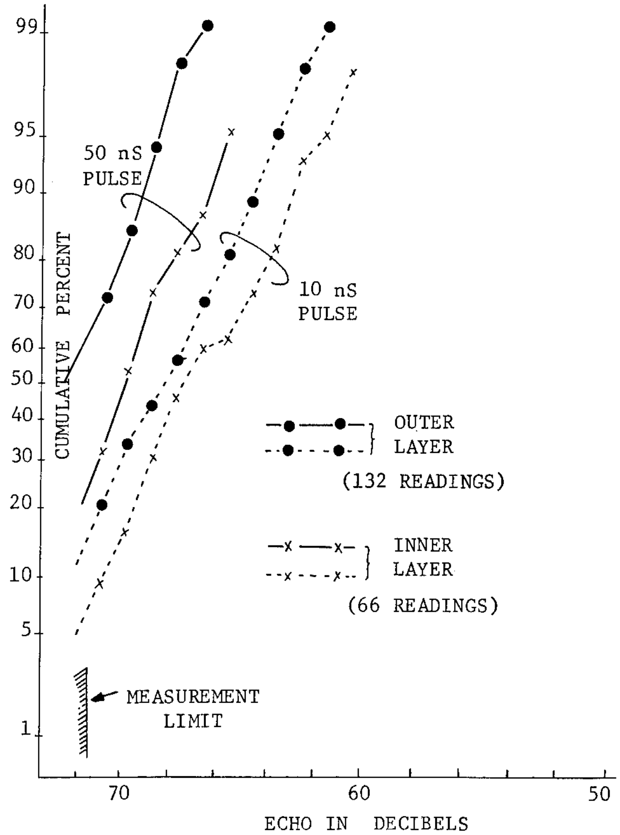


FIG. 4 DISTRIBUTION OF THE WORST INTERNAL ECHO ON FACTORY LENGTH

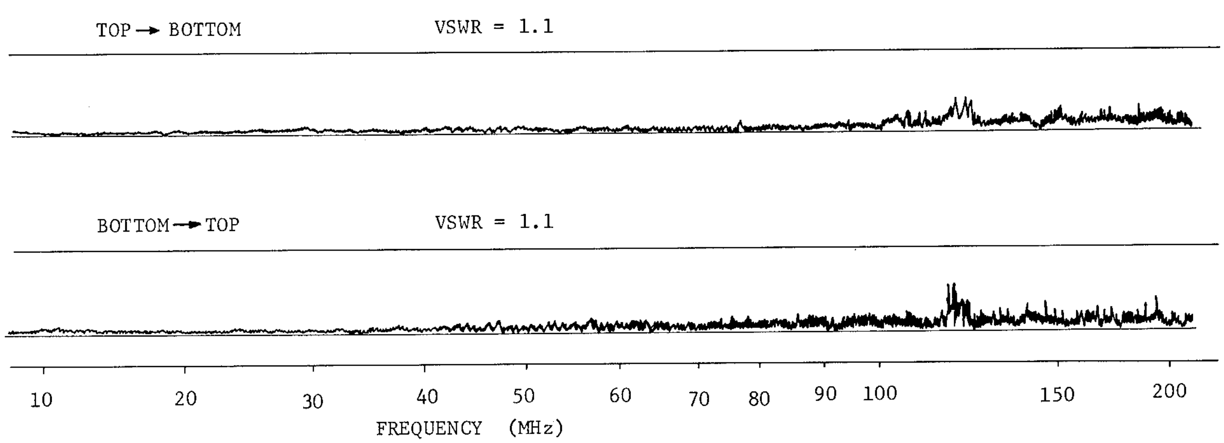


FIG. 5 AN EXAMPLE OF VSWR OF THE 18 CORE COAXIAL CABLE

Crosstalk characteristics of the 18 core coaxial cable was as excellent as one layer type coaxial cable containing less than 12 cores. As the 375 type coaxial core has a small gap along a longitudinal butt seam of copper tape, deterioration of crosstalk at high frequency has been anticipated because of the electro-magnetic leak from the seam. However, such a phenomenon has not been observed by the measurement of crosstalk up to 60 MHz.

Other electrical characteristics such as high voltage resistance and end impedance, and mechanical characteristics such as bending test, installation test and rewinding test were also inspected. This type of cable was proved to be excellent.

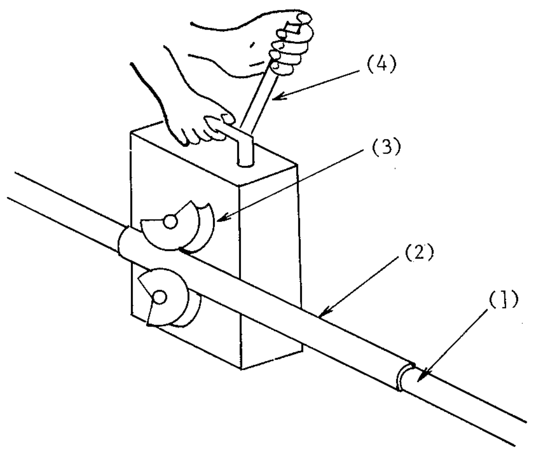
Splicing Method

For the splicing of the 375 type coaxial core in Japan, the "C type splicing method" has been adopted, in which the center conductors are crimped into the center conductor sleeve, the outer conductor and steel tapes are compressed between the steel bushings and the copper sleeves with a sleeve roller as shown in Fig. 6. Figure 7 shows the construction of the C type method.

However, it is thought that this method is not suitable for such a multi-core cable as a 18 core coaxial cable, because the usage of the sleeve roller requires much skillfulness and much space on both sides of the spliced core. To solve these problems, two methods have been developed: one is an "Improved C type method" and the other is an "M type method".

Improved C type method

Instead of a sleeve roller in the conventional C type method, a press pinch has been newly developed, to compress the copper sleeve efficiently. In this case, the splicing materials are the same as in the conventional C type method.



(1) COAXIAL CORE
(2) OUTER CONDUCTOR SLEEVE
(3) SLEEVE ROLLER
(4) RATCHET HANDLE

FIG. 6 SLEEVE ROLLER

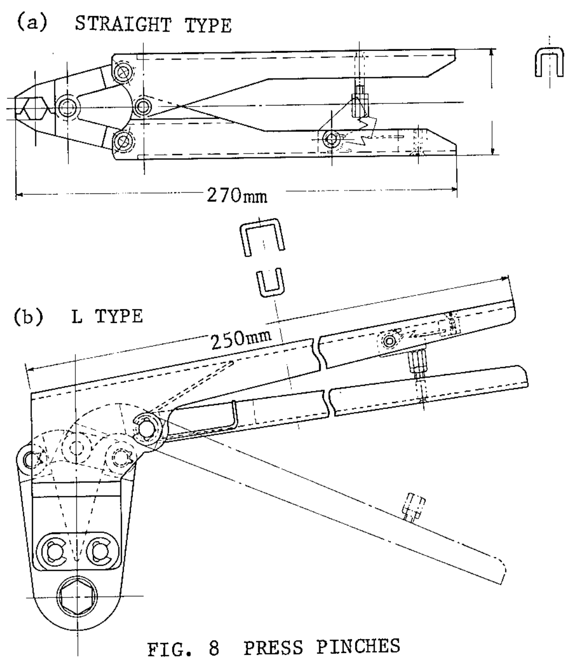
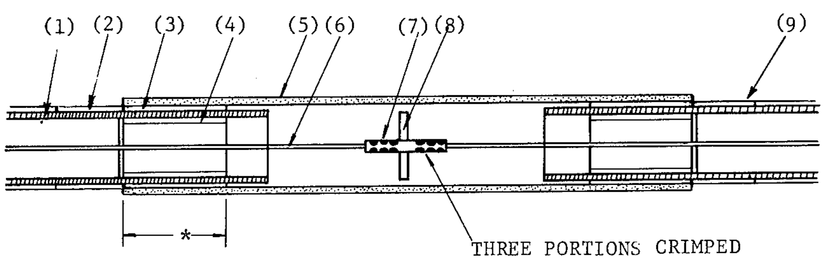


FIG. 8 PRESS PINCHES



(1) OUTER CONDUCTOR
(2) GUMMED PAPER
(3) COLLAR
(4) BUSHING
(5) OUTER CONDUCTOR SLEEVE
(6) INNER CONDUCTOR
(7) INNER CONDUCTOR SLEEVE
(8) INSULATOR
(9) INSULATING PAPER

* (A) UNIFORMLY COMPRESSED WITH A SLEEVE ROLLER (IN CASE OF CONVENTIONAL METHOD)
(B) THREE PORTIONS CRIMPED WITH A PRESS PINCH (IN CASE OF IMPROVED METHOD)

FIG. 7 C TYPE SPLICING METHOD

In order to compare the operation efficiency when using press pinches, two different types were made and tested: L type and straight type as shown in Fig. 8. After some detailed experiments, it was proved that the cores spliced with the new tools had mechanically and electrically better characteristics than those with the conventional method. Furthermore, the L type was considered to be a little better than the straight type, because the L type was more convenient when the effective space between the core and manhole wall or other obstacle was very narrow. This new L type tool has been still further improved and it is now used on commercial test.

M type method

The C type method has the following demerits.

(1) It is difficult to dismount the compressed sleeves.

(2) The outer diameter of the jointing part becomes very large, because a wide space is required between adjacent cores for using a sleeve roller, and one layer arrangement of the cores becomes necessary.

(3) It is difficult to keep the bending radius more than 15 cm, because enough straight portion of the core is required for the movement of the copper sleeve while mounting the splicing materials.

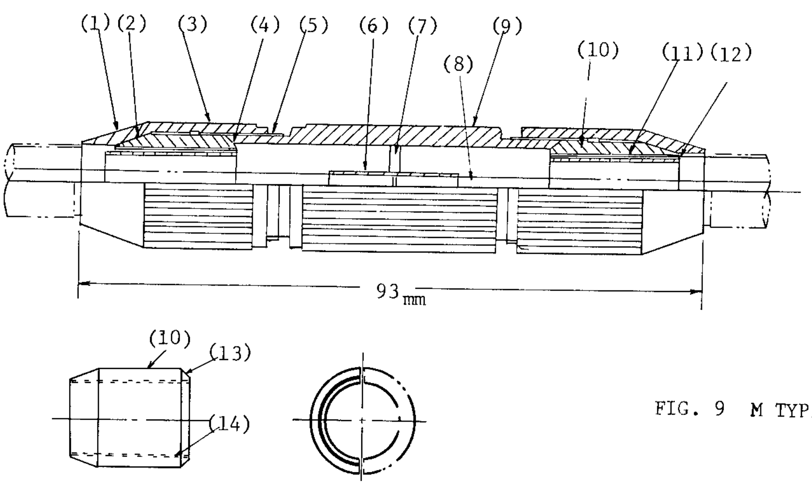
For the improvement of these problems, a mechanical connector method that is called "M type splicing method" has been developed as shown in Fig. 9. In the case of applying it to the 18 core coaxial cables, the results of the experiment are shown in Table 5. With this method, the length of the splice becomes much shorter and two layer arragement becomes possible. The outer diameter of the splice portion becomes much smaller and the bending radius becomes much larger in case of the two layer arrangement.

Characteristics

The test data on the electrical characteristics, for example the reflection coefficient, and on the mechanical characteristics, for example the tensile strength of the splicing portion, proved that these new type splicing methods have excellent properties.

Termination

Figure 10 shows a conventional method for coaxial cable termination in the control station. A multi-core coaxial cable is spliced to each single core which is terminated several meters apart. In the case of termination of so many cores as in the 18 core coaxial cable, the construction becomes very complicated and troublesome because the work must be carried out on a cable rack. Electrical characteristics especially in high fre-



(1) OUTER SLEEVE
(2) TAPER
(3) SCREW THREAD
(4) TAPER
(5) SCREW THREAD
(6) CENTER SLEEVE
(7) INSULATOR
(8) INNER CONDUCTOR
(9) BODY
(10) SEPARATED COLLAR
(11) OUTER CONDUCTOR
(12) BUSHING
(13) TAPER
(14) SCREW THREAD

FIG. 9 M TYPE SPLICING METHOD

Table 5 Comparison of M Type & C Type Splicing Methods

Items		M Type Method		C Type Method
Time Required for 18 Cores		5 hr 50 min		6 hr 10 min
Outer Diameter of Core Arrangement	Core Arrangement	1 Layer	2 Layers	1 Layer
	Maximum	200 mm	136 mm	203 mm
	Minimum	180	125	195
	Average	190	130	198
Length of Splicing Portion		580	520	640 - 800
Radius of Curvature of Core		170 - 370	290 - 300	170 - 290

quency such as 60 MHz may also be wrong, as two splicing points are very closed.

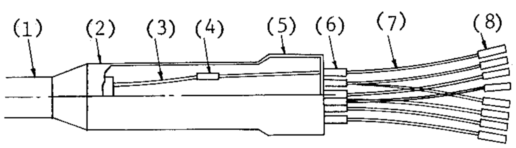
A new termination method has been developed for the purpose of the improvement of the following items.

(1) To eliminate the splice between single core and main cable core.

(2) To simplify the splicing operation by means of prefablicating the splicing box.

Several types of splicing boxes were designed and some of them were manufactured on a trial basis and tested. Examples of them are shown in Fig. 11. The rectangular type was designed, aiming at the stability of structure and the facility of connecting coaxial cords from a viewpoint of each relative position of a terminal box and repeater equipment. The connecting terminals were mounted on the side faceplate. Therefore, this type was larger than the cylindrical type. In case of the cylindrical type, cores can be smoothly bent because the terminals are mounted on the front of the box.

As a result of the field test of these types, the cylindrical type was proved to have excellent characteristics. The summary of a comparison of the improved method and the conventional method is indicated in Table 6. This type of termination method is anticipated to be in commercial use in the near future.



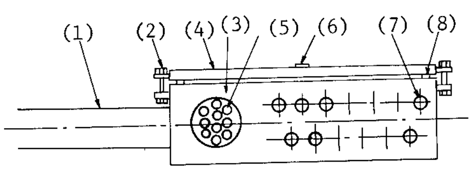
(1) 18 CORE COAXIAL CABLE
(2) MAIN LEAD SLEEVE
(3) COAXIAL CORE
(4) SPLICE
(5) LEAD SLEEVE FOR BRANCH
(6) SMALL LEAD SLEEVE FOR BRANCH
(7) SINGLE COAXIAL CORE
(8) TERMINAL JOINT

FIG. 10 CONVENTIONAL TERMINATION METHOD

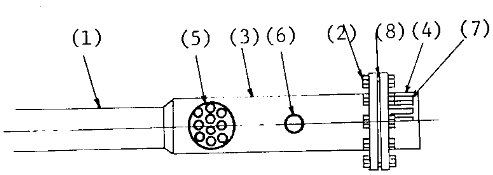
Table 6 Comparison of Two Types of Termination Methods

Items	Improved Method	Conventional Method
Type	Prefabricated Cylindrical Type	Branched with Single Core
Time for Termination	9 hrs	30 hrs
Echo with 50 nS Pulse at Terminal	59 dB	43 dB
Necessity of Single Core Cable	None	Required
VSWR	Small	Large
Kind of Materials	Few	Many
Length of Terminal Head	450 mm	930 mm*
Weight	27 kg	41 kg

*Length only contains main & branch lead sleeves.



(b) RECTANGULAR TYPE



(a) CYLINDRICAL TYPE

(1) 18 CORE COAXIAL CABLE
(2) BOLTS AND NUTS
(3) TERMINATING BOX
(4) COVER
(5) TERMINALS FOR INTERSTICE QUADS
(6) GAS VALVE
(7) TERMINALS FOR COAXIAL CORES
(8) GASKET

FIG. 11 IMPROVED TERMINATION METHODS

Stub Cable

A main cable and a repeater box are connected with a stub cable in a manhole. The construction of the conventional stub cable core has been a polyethylene jacketed (about 0.6 mm thickness) 375 type coaxial core. The allowable bending radius of this type of core and cable has been limited to 15 cm and 40 cm, respectively. But it is desired that the allowable bending radius is kept as small as possible, especially in the case of larger size cable.

Therefore, a new type of stub cable[3] has been developed, the construction of which core is 2.52 mm annealed copper center conductor, warty poly-

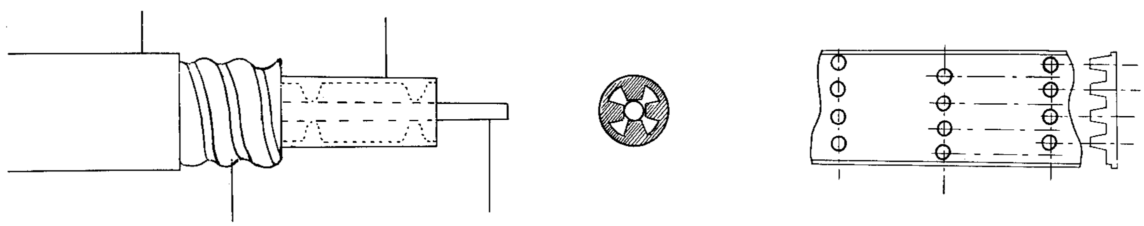
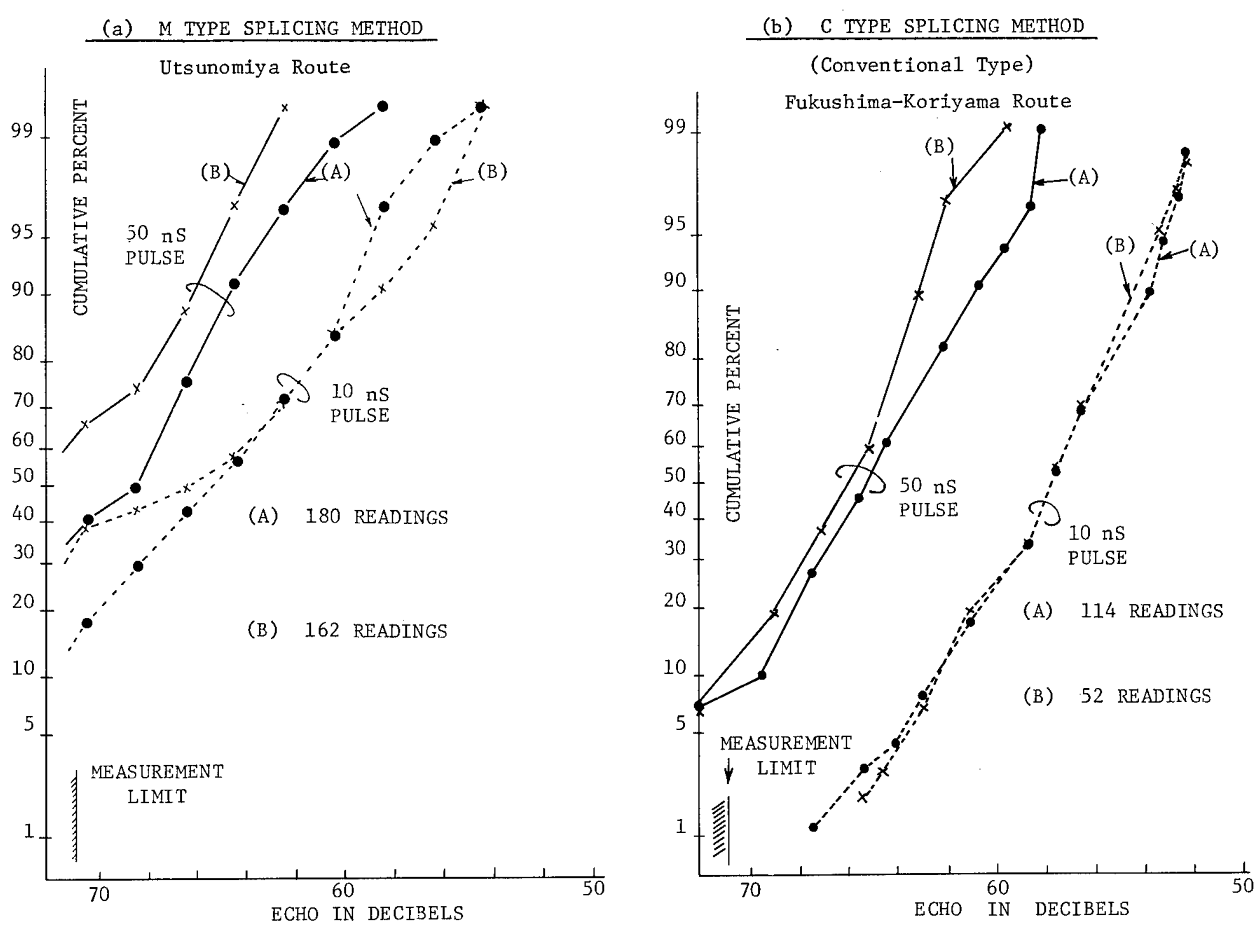


FIG. 12 8.6 MM CORRUGATED COAXIAL CORE FOR STUB CABLE



(A) indicates splicing points between two different pieces of cable which are allocated at the factory.
(B) indicates splicing points within the same piece of cable which is separated at the construction site.

FIG. 13 DISTRIBUTION OF PULSE ECHO AFTER INSTALLATION

ethylene insulation, corrugated and welded copper outer conductor, and natural colored polyethylene jacket, as shown in Fig. 12. This type of the coaxial core is very tough because the outer conductor is welded and corrugated. 4, 6 and 8 core coaxial cables were manufactured and investigated. They are certified to have very excellent characteristics. This cable will be useful for stub cable in narrow manhole for the 60 MHz system.

Data Obtained After Installation

About 50 kilometers of the 18 core coaxial cable have been constructed, in 6 sections for commercial test. The authors selected a route (Utsunomiya route) among them and measured precisely the electrical characteristics on the cables and the splice points of the route. The reason why we selected the route is that (1) M type splicing method is introduced and (2) the length of the route is short enough to measure all the cable pieces conveniently.

Figure 13 (a) is pulse echo distribution pattern measured by using 10nS and 50 nS pulse on M type splicing points. For comparison, pulse echo on C type splicing points from another route (Fukushima-Koriyama route north of Tokyo)[4] is indicated together in Fig. 13 (b). From these measured values the results are the following.

(1) The distribution patterns of pulse echo on the splicing points are almost the same in both cases of C type and M type, and the standard variation is 4.5 - 5.0 dB.

(2) The M type is about 4 dB in the case of 50 nS and about 6 dB in the case of 10 nS better than the conventional C type in average.

The internal pulse echo within cable pieces did not deteriorate from the factory lengths.

In the other measured data on electrical properties such as VSWR, crosstalk, attenuation, high voltage resistance, and so on, no problem was found.

Conclusion

It was proved that the 18 core coaxial cable and associated accessories mentioned above have enough electrical and mechanical properties for the C-60M system. The construction will begin in 1972 for a commercial test of the C-60M system using the 18 core coaxial cable between Tokyo and Osaka in expectation of mass communication media for the area between Tokyo and Osaka. The long term reliability and practical system performance will be carefully investigated throughout the commercial test.

Acknowledgement

The development has been carried out by a collaborating team consisting of Nippon Telegraph and Telephone Public Corporation and Sumitomo Electric Industries, Ltd. as well as Furukawa Electric Company, Ltd. and Fujikura Cable Works, Ltd. The authors should like to express their appreciation to the people concerned for their collaboration. The authors also should like to express their gratitude to the Cable R & D group of the Electrical Communication Laboratories of N.T.T.P.C. for their major activities in the development of the C-60M system and the stub cable.

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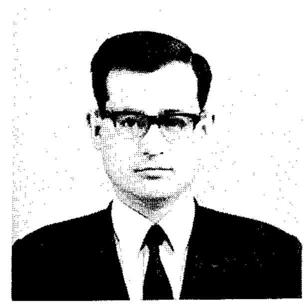

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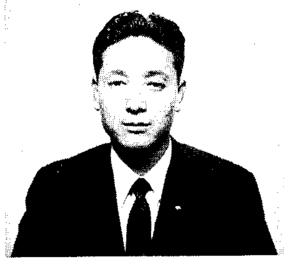

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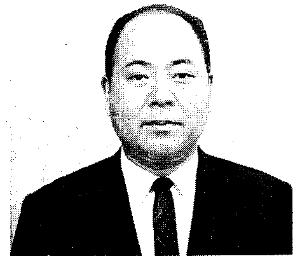

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FUSED DISC COAXIAL FOR BROAD BAND TRANSMISSION

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Introduction

With increasing exploitation of the bandwidth up to 300 MHz, high electrical uniformity is probably the most important prerequisite for broad band transmission lines. This uniformity applies to impedance and attenuation within cable lengths and from reel to reel of cable. The requirements become even more stringent as the bandwidth is increased. Since shorter wave lengths are involved at higher frequencies, any mechanical irregularities in the cable will have a significant effect on transmission properties. It was the objective, therefore, to design a cable which has a higher level of mechanical uniformity to achieve a better electrical performance. Such a cable is described in this paper.

The cable incorporates the excellent electrical features of the air dielectric cables and the structural characteristics of the foam polyethylene-aluminum sheathed cables (Figure 1). Adhesive copolymer discs are fused to the inner and outer conductors to provide individual, closed compartments which are sealed against moisture. The discs are spaced to provide proper mechanical support for the aluminum outer conductor.

An immediate application of this cable is seen for the "Cable TV" industry. Comparisons with presently used foam polyethylene-aluminum sheathed coaxials are presented and trial installations and field experiences are reviewed.

Extension of the application of this coaxial into the field of long haul multi-tube cables is also considered and to this end the crosstalk and the effects of assembling the tubes into a multitube configuration on SRL, impedance and echo are examined.

Theoretical and Practical Design Considerations

Present-day cable making technology allows for good control of the dimensions and resistivities of metal conductors. However, the state of the art[1, 2] of extruder technology, coupled with the additional problems of chemically blown foam dielectrics makes a high degree of uniformity almost impossible to achieve. It was therefore concluded that the application of a dielectric had to be accomplished by a more precise process. Precision molding of a solid plastic material at regular intervals was chosen and low attenuation realized by inclusion of air spaces between discs.

As previously stated, the initial design of this cable was intended for application in the cable TV industry and the following list of factors, not in any particular order, were considerations in the development.

1. High uniformity.
2. The same outside diameter as standard foam-aluminum sheathed cables.
3. Low cost.
4. Characteristic impedance of 75 ohms.
5. Low attenuation.
6. Satisfactory handling and mechanical sturdiness.
7. Imperviousness to moisture.
8. No longitudinal water path if mechanical fault occurs.
9. Elimination of the need to pressurize.
10. Compatibility with existing amplifiers and other hardware.
11. Low resistance path for amplifier powering.
12. Light weight.
13. Minimum radiation.

Compromises were necessary as in any design. This was especially true for the mechanical and the electrical objectives. For example, mechanical properties improve as disc spacing is reduced. However, for a fixed outside diameter and 75 ohm impedance, reduction of disc spacing necessitates a smaller inner conductor diameter which increases attenuation. Attenuation would be further increased as a result of higher dielectric losses caused by the frequent spacing of the discs, which in turn produces a steeper attenuation slope. A corrugated outer conductor would enhance the flexibility, however it would not only present a moisture path along the cable and at connector locations, but, even more significantly, would increase the difficulty of maintaining the desired control of the outer conductor dimensions.

Considering the fundamental electrical objective of low attenuation, S. A. Schelkunoff[3] has shown that for any coaxial outer conductor at any given frequency there is a wall thickness which will yield a minimum resistance. This optimum thickness is obtained when the real and imaginary parts of the diffusion constant are equal to $\pi/2$. As the outer conductor is made thicker than optimum, the resistance actually increases. This

results in a penalty of a few percent.

From Equation 1 it is apparent that an outer conductor of aluminum (ρ = 2.828 microhm-cm) has an optimum thickness at 5 MHz of 2.3 mils while at 300 MHz it is only 0.30 mils. It is clear that it is impossible to satisfy optimum outer conductor thickness requirements in a broadband system, especially if the band covers several frequency decades. Also, the above thicknesses would be inadequate from a mechanical standpoint and there are other considerations favoring a greater thickness of the outer conductor wall such as control of dimensions for electrical uniformity, noise pickup and radiation.

The high frequency attenuation relationship[4] in terms of dimensions and physical characteristics of the materials is given in Equation 2 while Equation 3 gives the condition for minimum attenuation. It can be seen that attenuation is a function of the diameter ratio (D/d) as well as the resistivities of the conductors. If the conductors are non-magnetic, such as copper or aluminum, then μ_D and μ_d are equal to 1.0, and if both center and outer conductor are of the same metal the optimum diameter ratio is 3.59. For the selected combination of an aluminum outer conductor (ρ_D = 2.828 $\mu\Omega$-cm) and a copper center conductor (ρ_d = 1.724 $\mu\Omega$-cm) the optimum diameter ratio is 3.81.

Figure 2 shows the relationship for non-magnetic materials between ρ_D/ρ_d and D/d for minimum α_C and Figure 3 is the relationship between D/d and the percent increase in α_C from optimum for an aluminum-copper construction (ρ_D/ρ_d = 1.64). It can be seen that the attenuation does not change very rapidly in the vicinity of optimum and therefore some latitude in selection of the D/d ratio is possible.

Fixing the D/d ratio to 3.81 and the characteristic impedance to 75 ohms and substituting into Equation 4, the resulting dielectric constant is 1.03. The dielectric constant of a disc insulated coaxial cable, assuming that the discs do not distort the electric field in their vicinity, can be determined from Equation 5. It follows, therefore, that for a dielectric constant (ϵ) of 1.03, and ϵ_m of 2.26 for the polyethylene discs, and a disc spacing (S) of 1.0 inch, the disc thickness must be 0.027 inch. This thickness is obviously inadequate for center conductor support. Again, a practical design was based on mechanical considerations and the final design for the initial cable size was adopted as having an outer diameter of 0.412 inch and an inside diameter of 0.362 inch, which were taken from the standard cable TV type. The disc thickness selected was 0.065 inch with a nominal spacing of 0.75 inch. These parameters were based on comprehensive testing which indicated that they represented a good compromise between mechanical and electrical considerations. This construction results in a dielectric constant of 1.11 which, substituted into Equation 4, results in a D/d ratio of 3.73 and an inner conductor diameter of 0.097 inch.

As previously indicated, a moisture tight cable structure is accomplished by the use of adhesive polyethylene discs (ethylene-acrylate copolymer). The high frequency dissipation factor of the dielectric material ($\tan\delta_m$) was derived from attenuation measurements on the above described coaxial cable and the method described in reference 5. The experimental data are given in Figure 4. Since $\tan\delta_m$ is fairly stable over the frequency range and averages approximately 0.00164, the dissipation factor of the cable ($\tan\delta$), determined from Equation 6, is 0.00028 which is equivalent to that of well made and dried standard foam polyethylene insulated CATV cables. This means that no change in equalizer networks is necessary.

The moisture seal between the center conductor and the discs is accomplished during the molding operation. The sealing between the discs and the aluminum outer conductor is accomplished by die sinking the tube to a compression fit over the discs and then flash heating it at 400°F.

A comparison of the maximum attenuation characteristics of the Fused Disc coaxial cable and the present standard foam insulated types are given in Figure 5. Curve A is the attenuation of the .412" Fused Disc coaxial with a copper or copper clad aluminum center conductor; Curve B, the .412" foam polyethylene cable and Curve C, the serrated seam .375" disc coaxial. Also for comparison, Curve A_1 is the attenuation of a Fused Disc coaxial with 100% aluminum center conductor. It can be seen that the attenuation of the Fused Disc with the copper or copper clad center conductor is 20% lower than the attenuation of the foamed cable of the same diameter and has the same slope. The comparison with the .500" foam insulated coaxial is given in Table I and shows the attenuation of .412" Fused Disc equivalent to the .500" foam cable.

It is apparent that the outer conductor has to be a homogeneous tube free from holes to keep radiation to a minimum. But in general, it is the surface transfer impedance[7] ($Z_{\alpha\beta}$) of the outer conductor that must be as low as possible across the entire frequency range of interest. From Reference 3 it can be seen that $Z_{\alpha\beta}$ is a function of attenuation (α_s), thickness, permeability and resistivity, as shown in Equation 7. It is evident that in the frequency range of interest (10 to 300 MHz) and a fixed outer conductor wall thickness, $Z_{\alpha\beta}$ is reduced if the properties of the outer conductor material provide a low K value in Equation 7.

Table II gives shield attenuation data for three of the most common outer conductor materials. Using the figure in Table II, K was determined for a shield 1 mil thick. These values at different frequencies of interest are given in Table III. It can be seen from this table that the steel has a distinct shielding advantage at higher frequencies but at lower frequencies heavier wall thicknesses of steel relative to copper or aluminum would be necessary for equivalency. A combination

of metals will improve the shielding because of the added attenuation and reflections at metal interfaces. It was decided to use the standard 25-mil wall of aluminum presently employed in the industry for the outer conductor since it is a good compromise between shielding efficiency and other essential properties for the cable TV frequency range.

The final consideration in the design of the Fused Disc cable was its corona and dielectric strength properties. Corona on the inner or outer conductor is objectionable because it generates high frequency noise which is superimposed on the transmitted signals, greatly reducing the signal to noise ratio. Using the well known expression[6] for potential gradient in a "perfect" coaxial structure, it can readily be seen in Equation 9 that the gradient which will cause partial or complete discharge is also a function of the D/d ratio. Since the maximum gradient is at the surface of the inner conductor, taking the derivative of g_r with respect to r in Equation 10 and setting it to zero provides an optimum D/d ratio of 2.72.

This optimum D/d ratio is substantially different from that required for optimum attenuation. However, from Figure 7, it can be seen that the discharge potential does not vary abruptly in the vicinity of the optimum ratio of 2.72 and that the .412" Fused Disc coaxial with a D/d ratio of 3.73 suffers only about a 4% penalty. Figure 7 is based on the assumption that the maximum gradient (g_r) for air at atmospheric pressure is 31 kV dc per centimeter.

Theoretically this cable should have a dielectric strength of 5 kV, however due to minor imperfections in the form of slivers, oxide inclusions, etc. on the center conductor this is not achieved in practice.

Electrical Performance

The theory and design were verified experimentally by laboratory tests on randomly selected samples of .412" Fused Disc jacketed and unjacketed cables and routine production tests on limited production runs totalling about 40 reels of cable, each containing about 2000 feet. These cables were made from the same lot of each material. The aluminum outer conductor was constructed from tube formed by both seam welding and seamless extrusion.

As was expected, the striking characteristics of the Fused Disc cable is its superb electrical uniformity within cable lengths as well as from one cable length to another. This is due to the dimensional precision of both conductors and the precision molding of the insulating discs.

The terminal impedance determined from the SRL tests across the frequency band 10 to 300 MHz for all cables produced to date has a standard deviation (σ) of 0.18 ohm. The standard deviation of jacketed and unjacketed cables taken separately is substantially less, only 0.11 ohm for each group. The comparatively high magnitude of the combined figure is the result of a lower average impedance for the jacketed cables, i.e. 74.85 ohms average for jacketed cables as compared to 75.05 ohms average for unjacketed cables. The decrease in impedance was due to the partial flattening of the cable caused by the tensions of re-reeling during the jacketing operation as well as by the heat of extrusion of the jacket.

In general, the terminal impedance of the inside end of the cable on the reel was found to be 0.10 ohm lower than that of the outside cable end. This is normal and is a function of the reel drum size and the axial cable tension at take-up. This difference diminishes, however, on unwinding, indicating that the compressive forces on the reeled cable can be kept sufficiently low so that the elastic limit of the outer conductor is not exceeded.

The important attenuation characteristics were determined by the insertion loss method in a 75 ohm system at 220 MHz on all cables produced. Attenuation across the frequency band from 10 kHz to 300 MHz was measured on a typical cable and data is presented in Figure 8. The measured values of attenuation at 220 MHz, normalized to 68°F, shows a maximum spread of 1%. This is small when one considers the uncertainty of the cable temperature during measurement, possible length errors and the accuracy of the production test equipment. Figure 9 provides the percent change in attenuation per degree fahrenheit versus frequency for the Fused Disc coaxial.

Analysis of the SRL levels measured from 10 to 300 MHz on approximately 40 reels of cable were found to be as follows:

	Unjacketed Cables	Jacketed Cables
Average, dB	40.0	40.1
Worst, dB	36.5	36.0
Best, dB	44 approx.	44 approx.

To preserve the high SRL uniformity of 40 dB, care in the handling of reels is required. Careless handling, or external damage, can lower the SRL levels substantially as shown above by the 36 dB figures. This, of course, holds true for cables of any design.

High frequency velocity of propagation was measured in the laboratory and was found to be 95%. The capacitance of the Fused Disc coaxial was 14.25 picofarads per foot.

The d.c. resistance of the solid copper center conductor of Fused Disc cables is 1.10 ohms per 1000 feet at 68°F. This is approximately 64% lower than the d.c. resistance of the .412" foam-aluminum coaxial and equivalent to the 0.500" foam-aluminum coaxial. The loop resistance is 1.54 ohms per 1000 feet which is approximately 7% higher than that of the 0.500" foam-aluminum cable.

The d.c. voltage breakdown of the Fused Disc

cable averaged 4 kV. It is of interest to note that the average voltage breakdown and standard deviation figures for both jacketed and unjacketed cables were identical. This implies that additional slivers (elemental metal filaments of conductors) are not produced by the re-reeling necessitated by the jacketing operation. Referring to Equation 12 in the Appendix, the k_p factor was reduced from an ideal value of 1.0 to 0.8. Since cables used for cable TV operate at potentials below 100 volts, the 4 kV dc breakdown strength of the Fused Disc coaxial design provides an adequate safety factor.

Insulation resistance (IR) measured on all cables at room temperature with a dc potential of 100 V, after an electrification period of 1 minute using production type test equipment averaged 5000 megohm-miles. These values were substantiated in the Laboratory on selected reel lengths using extremely stable power supplies and noise filters, however with longer electrification periods, the values of IR were considerably higher. Increasing the test potential yielded the same results until partial discharge level (corona) was reached, at which time, the IR values dropped sharply and became erratic or fluctuated with time.

Physical Performance

Sealing against moisture was achieved by fusing disc insulators to both the inner and outer conductors thereby forming hermetically sealed compartments. The seal was checked on every length of cable manufactured by taking a 6 inch sample from the inside and outside end on each reel and subjecting them to 25 psi of air pressure for 15 minutes applied at one end of the sample. The opposite end of the sample was immersed in water and checked for air bubbles, which, if present, would constitute a seal failure. Not one sample has failed this test.

In the Laboratory, samples of .412" Fused Disc cable, 12 inches in length, were tested for moisture or water ingress using a time domain reflectometer (TDR) test set. The open-circuited end of the cable sample was immersed in water and the impedance monitored with time. As indicated in Figure 10, the TDR impedance trace did not change after 3 weeks of testing at which time the test was discontinued. The downward swing at the end of the trace due to water bridging the cable conductors did not shift towards the TDR input end, indicating that the water did not penetrate past the first disc. Also, lack of noticeable change in the slope of the impedance trace indicated no discernible moisture permeation across discs.

Pull-out test results given in Table IV show a high degree of adhesion between the discs and the inner and the outer conductors. These tests were performed on a number of cable samples which were manufactured at different times. There were little, if any, differences in results from cable to cable. Experimental cables produced show no change in the degree of adhesion after a period of 18 months. Thus, the adhesion to the copper center conductor per disc averages about 20 lbs while that to the aluminum outer conductor about 6 times as great. Since the ratio of the circumference is $.362\,\pi / .097\,\pi = 3.7$, higher adhesion to the outer conductor is due to the greater affinity of the polyethylene copolymer to aluminum than to copper.

This consistency of disc adhesion within cable lengths and from cable to cable is attributed to the precision molding of the discs and the uniformity of the outer conductor dimension. In the foam-aluminum coaxials, the variation in pull-out strength is due to the variation in the insulation diameter from run to run and consequently a varying degree of squeeze by the aluminum sheath. If the degree of squeeze was held constant by varying the aluminum sheath outside diameter, the spread of characteristic impedance and attenuation from one run to another would increase. It is partially for the above reason that a $\pm$ 2 ohm impedance tolerance is required for foam-aluminum cables.

The compression and impact studies shown in Figures 11 and 12, respectively, indicate that some improvement is obtained with the jacketed construction. It can also be seen that the higher the SRL uniformity of the cable, whether Fused Disc or foam type, the more susceptible it is to dB degradation for a given damage, although of course the reflected voltage from the damage remains the same. Figures 11 and 12 show clearly that there is little difference between the Fused Disc and the foam type cables as far as resistance to external damage is concerned for 40 dB SRL cables. On lower SRL cables, the physical deformation resulting from impact and compressive forces does not readily appear as an electrical fault since this fault is masked by the higher reflection voltage levels superimposed thereon. After substantial damage, the foam core, however, provides greater resistance to further abuse.

Laboratory studies of cable bending around mandrels are presented in Figure 13 and show results similar to those for impact and compression. The minimum mandrel bending diameter for the .412" Fused Disc cable was found to be about 6 inches as compared to 2.5 inches for the .412" foam cable before catastrophic failure occurs. Although the foam cable can be bent safely around a smaller diameter, the normal standard diameters employed (10 inches) in the industry have no appreciable effect on either cable. The tests were conducted with light axial tension on the cable. If this tension is increased, the cables can be bent around somewhat smaller mandrels.

If the minimum bend diameters are exceeded, the outer aluminum conductor of the cables will jackknife causing faults. In the Fused Disc this often leads to shorts between conductors and a 100% reflection.

It was found that physical change in the cable structure caused by bending is first

observed electrically. Bent sections of cable flatten during bending and appear as electrical faults. The minimum bending diameter required to observe physical damage is smaller than the minimum electrical bending diameter. That is, the smaller the bending diameter, the greater the flattening. This is more apparent on high SRL quality cables.

The study of the life of expansion loops is presented in Figure 14 wherein the details of the expansion loop are also shown. It can be seen that for an excursion of 2" or less the Fused Disc cable loop has a longer life than its foam-aluminum counterpart. If excursions greater than 2" are allowed, both cables will have short lifetimes with the foam cable somewhat better. This behavior is due to what can be termed "precorrugating," i.e. a slightly higher outside cable diameter over discs than between discs. When deformation (bending) is moderate, "precorrugation" facilitates an even distribution of the stresses. If the excursion level is increased, this mechanism ceases to work and the stress is concentrated at the weakest point.

The weight of .412 Fused Disc jacketed cable is roughly 35% less than its .500" foam electrical counterpart which has significant implications on handling.

Field Evaluation

The foregoing data indicated that the Fused Disc cable was of a sound design. However, laboratory testing cannot simulate actual field conditions and the next stage of investigation was to arrange for field installations.

The first installation was made in Orange, Texas, located on the Gulf coast and the Lousiana-Texas border. The cable employed an 0.097" solid copper clad aluminum center conductor. A 35-mil wall of black high molecular weight polyethylene was extruded over the aluminum sheath because of the salt air atmosphere.

SRL, echo and impedance were tested at the plant, on site prior to installation and after installation. The cable was installed by an independent contractor whose experience was entirely with foam-aluminum cable. The installation was made with no splices between amplifier sections. Where there were parallel runs, distribution cables were installed together with the Fused Disc coaxial and in one instance as many as three distribution cables were installed.

The cables were installed aerially from a stationary reel trailer by pulling from one amplifier location up through rollers at each pole and one or two rollers per span, depending on the length, to the next amplifier location and then back lashing to the reel trailer location. Expansion loops were made at each pole using a makeshift forming tool made from half of a 10 inch aluminum pulley.

Measurements were made at ground level by either connecting the bridge to the cable when the cable was cut at ground level or by using long leads between the SRL test set and the bridge. The leads consisted of 50 feet of RG-59 which upset the attenuation calibration of the SRL test set. The reference branch remained unchanged and relatively flat, but the unknown branch, containing the SRL bridge with its cable terminals shorted (or open-circuited) for calibration purposes exhibited a characteristic downward slope corresponding to the attenuation losses of the leads over the frequency range (Figure 15). This imposed some difficulties in the evaluation of the cable SRL, however this problem was alleviated by inserting the same length of RG-59 in the reference branch. SRL was determined by matching the bridge and the end termination to the cable using walkie talkies for communication.

There were several places where the cable was subjected to 90° bends and in one location the cable was pulled through a double 90° bend in a Z configuration, however no degradation occurred as a result of the installation. Figure 16 shows typical SRL test results. Figure 17 is an example of the SRL pattern caused by a fault when the cable was physically damaged. The cable interfaced with the amplifiers, splitters and power supplies using standard open front end .412" connectors. Drip loops were made in the cable ends which mated to the hardware. It was noted that the connectors were applied to the cable very quickly since with a cut around the aluminum sheath using a tube cutter, the aluminum and one disc can be removed without the necessity of cleaning the center conductor as required with the foam-aluminum cables.

The system was turned on and the TV picture at the end of the trunk run was observed and judged to be equal to that at the head end. Eight months after installation and after being subjected to high winds and heavy rains, the system continued to provide excellent service.

The second installation was made in Jefferson City, Missouri. At this location, jacketed .412" Fused Disc was used as the trunk cable and unjacketed .412" Fused Disc as the distribution (feeder) cable. For this installation, the center conductor was solid copper. The first installation indicated that jacketed cable used for the trunk can be installed without difficulty. The purpose of this installation was to learn whether unjacketed Fused Disc cable can be installed and whether it can be used for distribution where it would be subjected to the many drip loops required with directional tap-offs every few hundred feet. The same testing program as in the first installation was followed here. The cables were tested at the site and tested again after installation. This cable plant was also an aerial installation installed by another independent contractor. The cable was installed employing the standard industry practices used for the foam-aluminum cables. The tap-offs were installed by Jefferson City TV personnel.

Summarizing the comments of the contractors, field personnel and the cable TV operator, it can be said that using standard methods this new product installs with no more difficulty than presently used foam polyethylene-aluminum sheathed cables except the comment was made that the expansion loop should be made more carefully. This, however, is of no concern provided a properly designed bending tool is used. The installation was completed without degradation of the excellent electrical characteristics of the cable.

Multi-Tube Cable Construction Evaluation

The cabling of coaxial tubes into a composite cable has its own particular set of problems. Therefore, in order to study these problems, two cables, each 1000 feet in length, were manufactured. These cables consisted of four .412" Fused Disc tubes cabled with crushed polyethylene tape fillers in the interstices. The direction of the cabling was right hand, but, since the tubes have no helical components to tighten or loosen, either direction could have been employed. The rigidity of the tubes and torsional twist considerations dictated the use of a floating carriage (planetary) type cabling machine. The torsional twist, determined by Equation 13a, and based on a mean diameter of .58 inch and a cabling lay of 42 inches, is only 0.1513° per inch, or 6.36° per cabling lay.

The fundamental SRL spike which is attributable to the cabling lay occurred at 135 MHz for all four tubes. Its second harmonic was of considerably lower amplitude. The SRL level of the cabling spikes, measured from both ends for each tube, averaged 29.8 dB with the maximum 25.0 dB and the minimum 33.7 dB; an example is shown in Figure 18. The outside cable end measured an average of 3.5 dB better than the inside end. The overall SRL level in the 10 to 300 MHz frequency band was degraded by cabling to 35.5 dB, worst case.

All the Fused Disc tubes were checked for pulse echo response using a 60 nanosecond at half amplitude sine-square pulse. The average echo of the 40 lengths produced was 69.5 dB down from the incident pulse and the worst 65 dB. After cabling, the worst echo of the four tubes was degraded to 60 dB. Pulse echo measurements were also conducted with narrower pulses which had frequency spectrums up to 60 MHz. The echo levels were substantially the same but the resolution improved.

The crosstalk coupling loss between the adjacent and the diametrically opposite .412" Fused Disc cabled tubes was measured between 10 kHz and 25 MHz and are given in Figure 19.

Conclusions

A new coaxial cable, herein referred to as Fused Disc by the nature of its construction, was developed and data presented, demonstrating that it meets the criteria established, as follows:

1. Excellent electrical uniformity.
   a. Maximum variation in attenuation from cable to cable of 1%.
   b. Characteristic impedance tolerance of $\pm$ 0.5 ohm.
   c. Worst SRL level of 36 dB individual cable and 40 dB average of all cables tested.
   d. Worst echo values of 65 dB down measured at the point of reflection.

2. Low attenuation.

   The attenuation of the .412" Fused Disc cable is equal to .500" and 20% lower than the .412" standard foam polyethylene-aluminum sheathed coaxials used in cable TV systems.

3. Compatibility with existing hardware.

   The attenuation slope is the same as the foam-aluminum cables permitting the same equalizers to be used. Standard .412" connectors presently used in the cable TV industry are available.

4. Satisfactory mechanical sturdiness.

   Two installations have been made with success.

5. Imperviousness to moisture.

   Laboratory tests and the weathering of installed cables prove the hermetic seal of individual compartments.

Acknowledgments

The authors wish to express their thanks to the Gulf and Western Company personnel, especially Mr. William C. Henchy, Vice President, for cooperation and help received in the field installation and evaluation of the Fused Disc coaxial.

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Table I

Attenuation versus Frequency

Frequency (MHz)	Maximum Attenuation (dB/100 ft) 0.500" Foam Aluminum	0.412" Fused Disc
55 (Channel 2)	0.66	0.64
83 (Channel 6)	0.81	0.805
100	0.90	0.89
175 (Channel 7)	1.22	1.22
211 (Channel 13)	1.35	1.36
250	1.50	1.48
300	1.65	1.63

Table II

Attenuation (α_S) in Shielding Materials versus Frequency

Frequency (MHz)	(nepers/mil) Copper $\mu = 1$ $\rho = 1.724\ \mu\Omega$-cm	Aluminum $\mu = 1$ $\rho = 2.828\ \mu\Omega$-cm	Iron $\mu = 100$ $\mu = 10.6\ \mu\Omega$-cm
0.001	0.01216	0.00949	0.04902
0.01	0.03845	0.03001	0.15501
0.1	0.1216	0.0949	0.4902
1.0	0.3845	0.3001	1.550
10.0	1.216	0.949	4.902
100.0	3.845	3.001	15.50
300.0	6.660	5.198	26.85

Table III

Factor K of $Z_{\alpha\beta}$

Frequency (MHz)	Copper	Aluminum	Iron
0.001	1.297	1.666	31.0
0.01	1.263	1.632	27.88
0.1	1.163	1.529	19.94
1.0	0.894	1.246	6.910
10.0	0.389	0.651	0.242
100.0	0.0281	0.0836	0.00001
300.0	0.00168	0.0093	--

Table IV

.412" Fused Disc Pull Out Test, pounds

		Original	70°C Aging		
			3 Days	7 Days	11 Days
A) Center conductor from cable sample containing 3 discs					
	Average	66.7	12.2	14.3	28.4
	Minimum	54	6.8	12.1	9.8
	Maximum	82	17.1	15.8	37
B) Disc from Aluminum Outer Conductor					
	Average	120.8	129.5	125.8	125.7
	Minimum	94	128	121	117
	Maximum	133	131	134	131

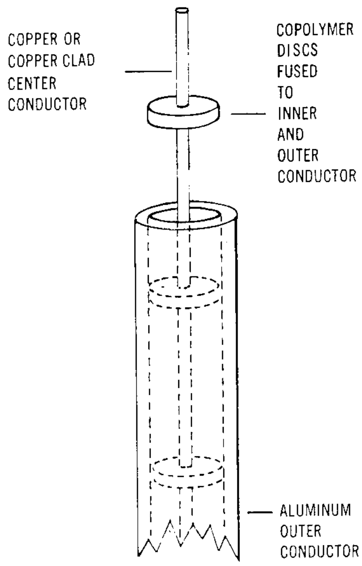


FIGURE 1
FUSED DISC CONSTRUCTION
(Not to Scale)

FIGURE 3

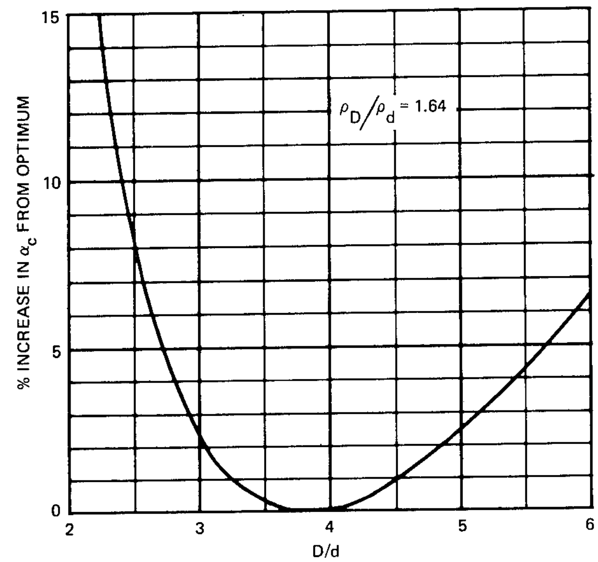


FIGURE 2

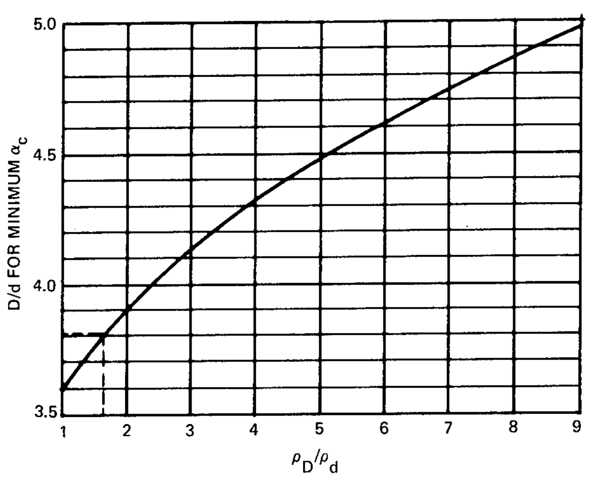


FIGURE 4

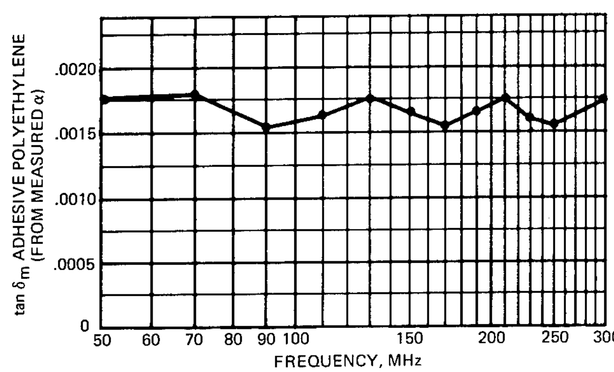


FIGURE 5

A - FUSED DISC WITH COPPER CENTER CONDUCTOR
A1 - FUSED DISC WITH ALUMINUM CENTER CONDUCTOR
B - .412" FOAM POLYETHYLENE COAX
C - SERRATED SEAM .375" DISC COAXIAL

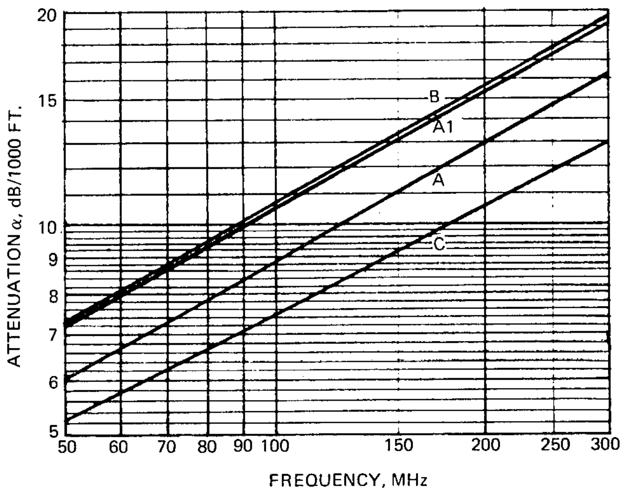


FIGURE 6

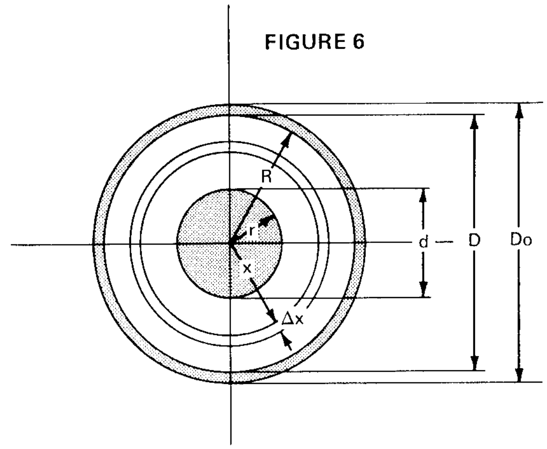
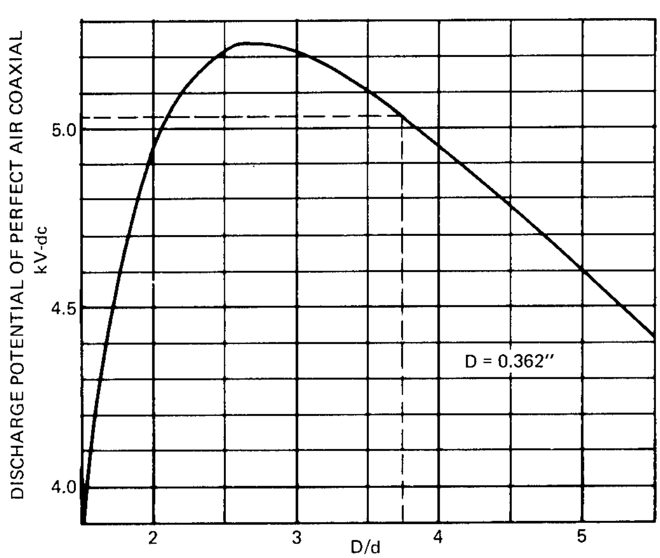


FIGURE 7



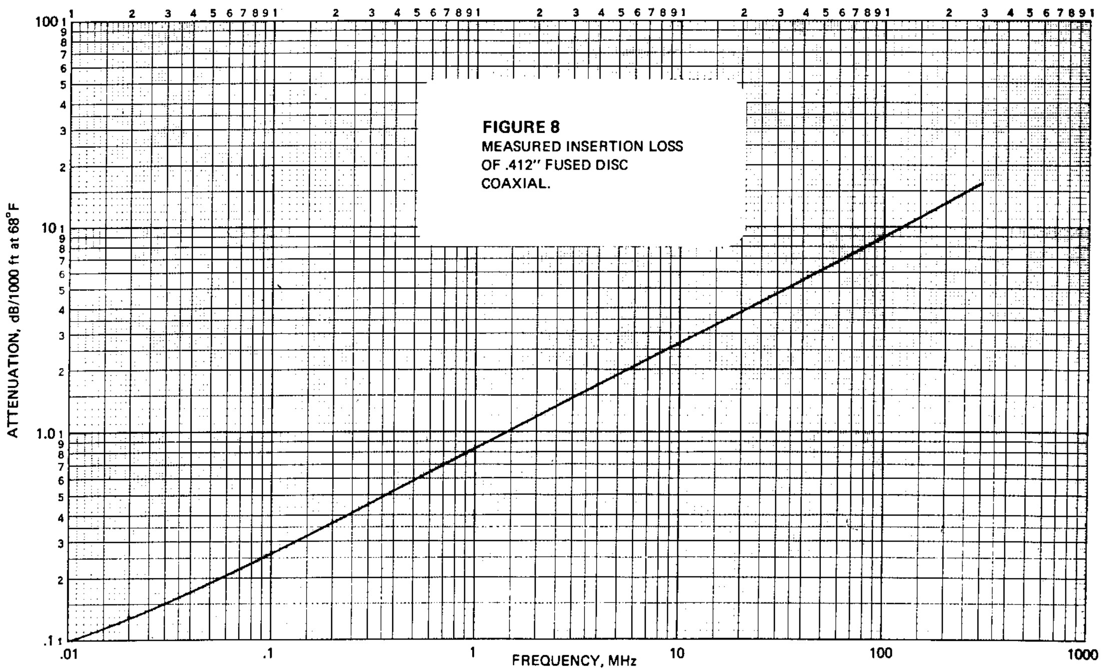


FIGURE 8
MEASURED INSERTION LOSS OF .412" FUSED DISC COAXIAL.

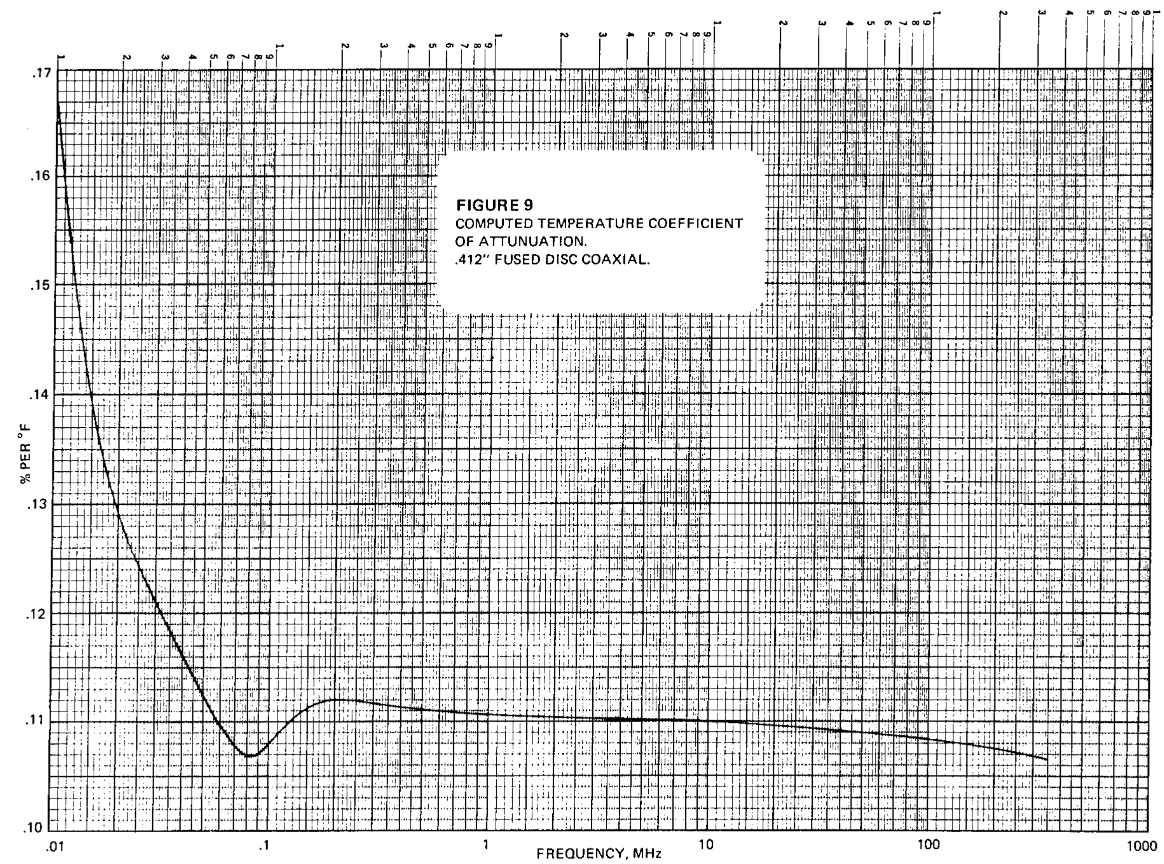


FIGURE 9
COMPUTED TEMPERATURE COEFFICIENT OF ATTUNUATION.
.412" FUSED DISC COAXIAL.

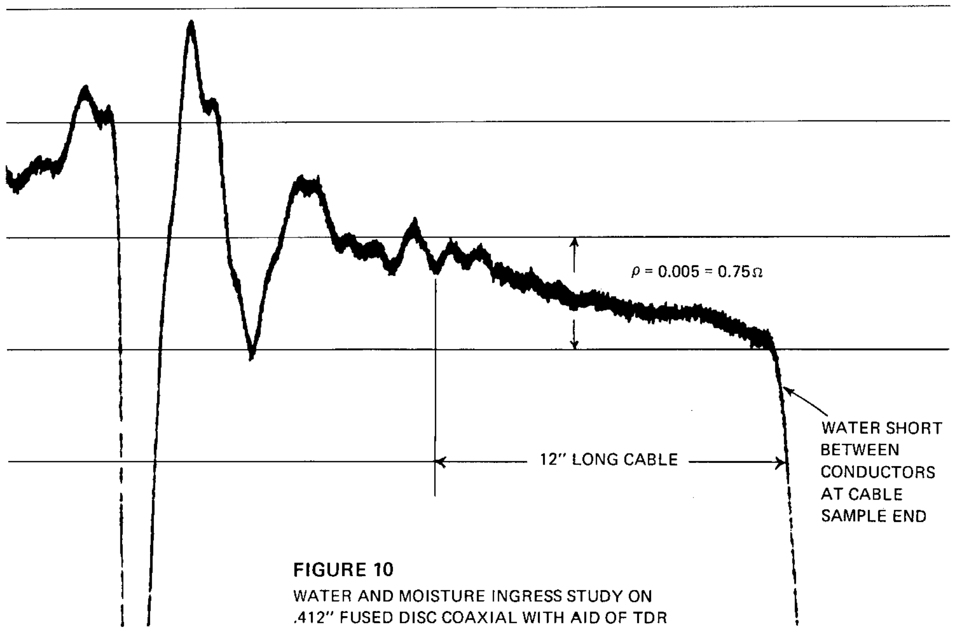


FIGURE 10
WATER AND MOISTURE INGRESS STUDY ON .412" FUSED DISC COAXIAL WITH AID OF TDR
(TDR trace, original & after 3 weeks of cable end immersion in water, i.e., no change)

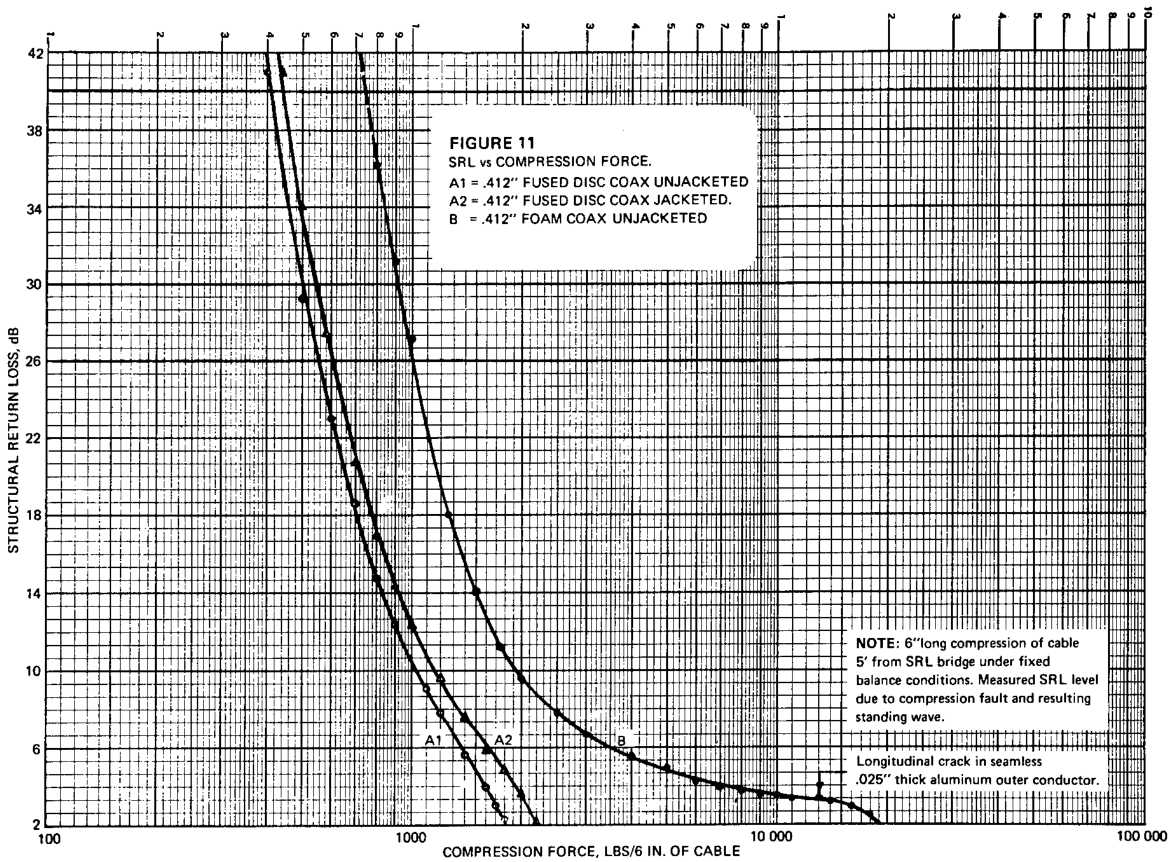


FIGURE 11
SRL vs COMPRESSION FORCE.
A1 = .412" FUSED DISC COAX UNJACKETED
A2 = .412" FUSED DISC COAX JACKETED.
B = .412" FOAM COAX UNJACKETED

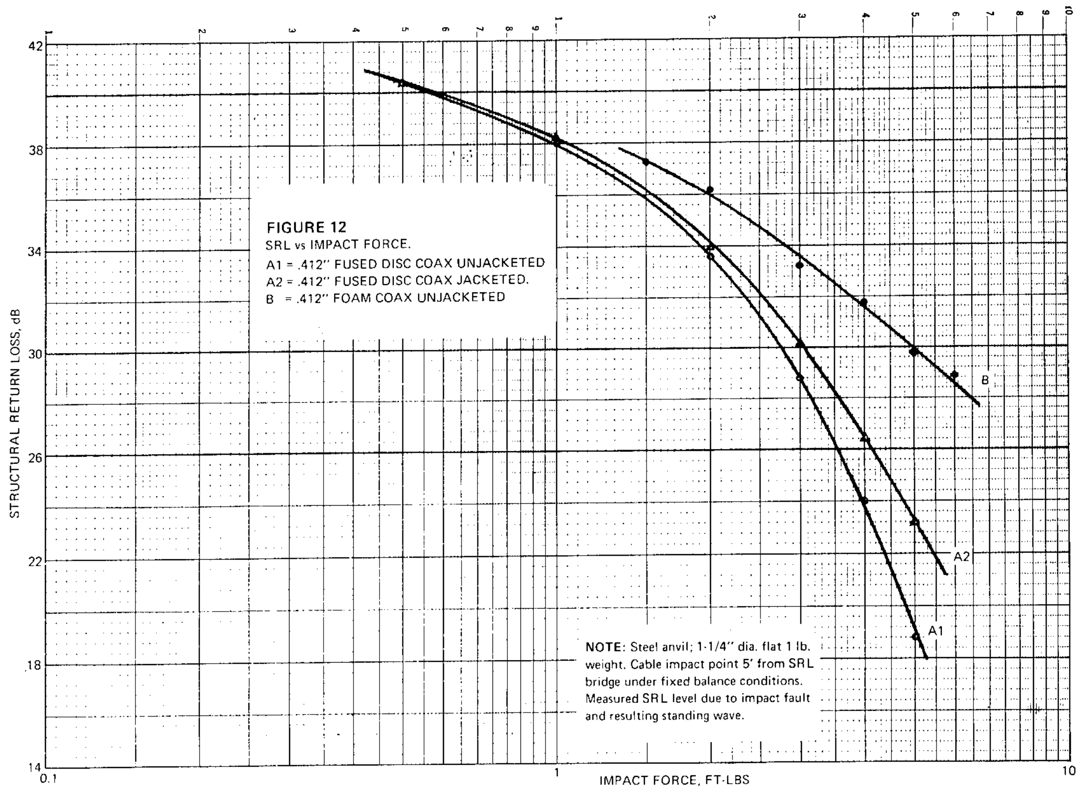


FIGURE 12
SRL vs IMPACT FORCE.
A1 = .412" FUSED DISC COAX UNJACKETED
A2 = .412" FUSED DISC COAX JACKETED.
B = .412" FOAM COAX UNJACKETED

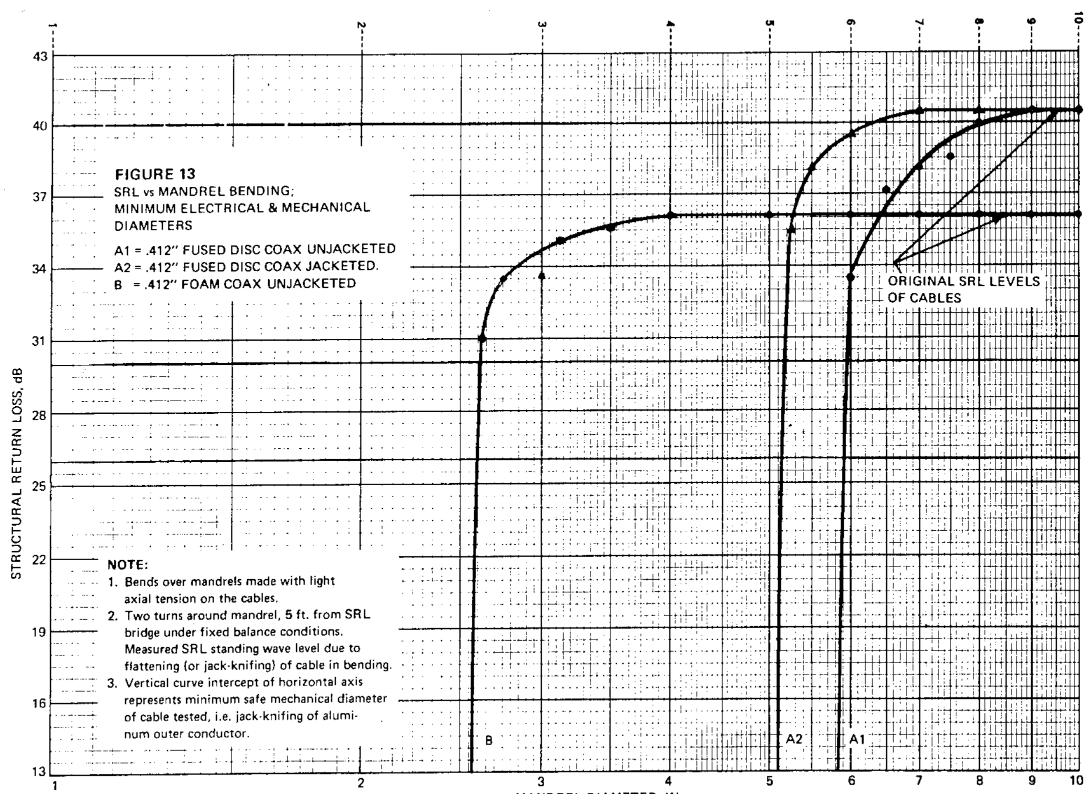


FIGURE 13
SRL vs MANDREL BENDING;
MINIMUM ELECTRICAL & MECHANICAL DIAMETERS
A1 = .412" FUSED DISC COAX UNJACKETED
A2 = .412" FUSED DISC COAX JACKETED.
B = .412" FOAM COAX UNJACKETED

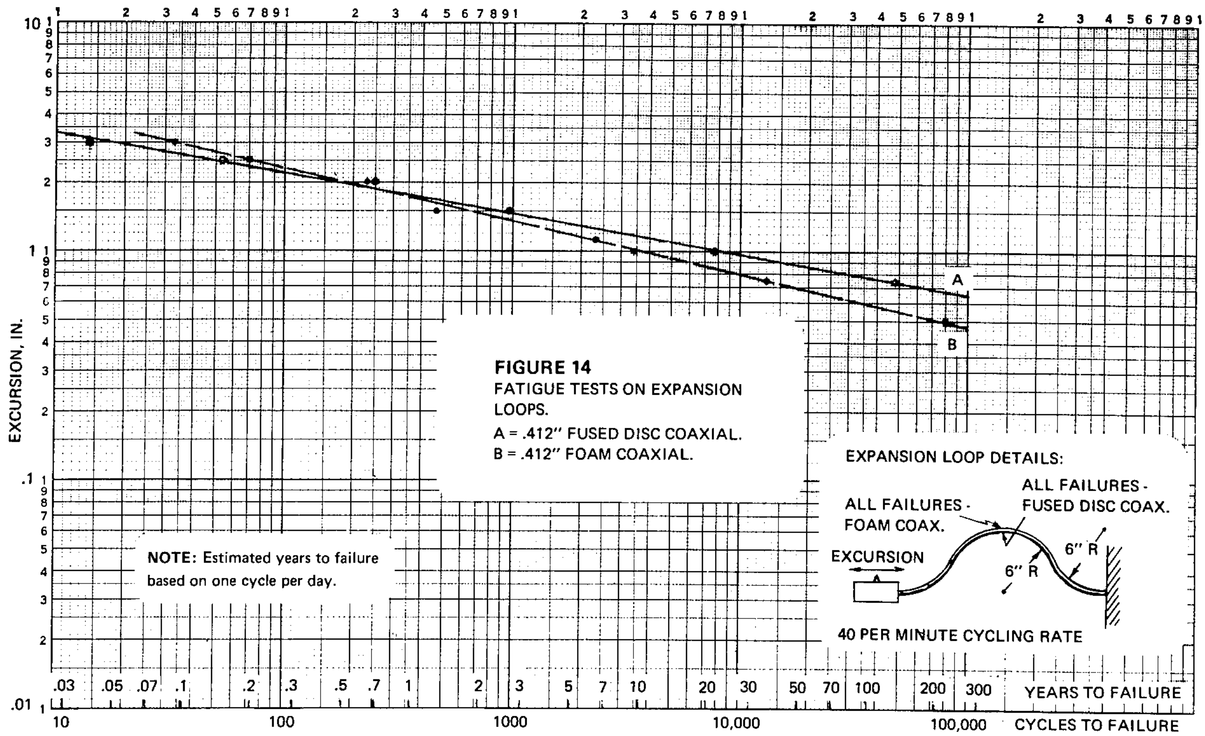


FIGURE 14
FATIGUE TESTS ON EXPANSION LOOPS.
A = .412" FUSED DISC COAXIAL.
B = .412" FOAM COAXIAL.

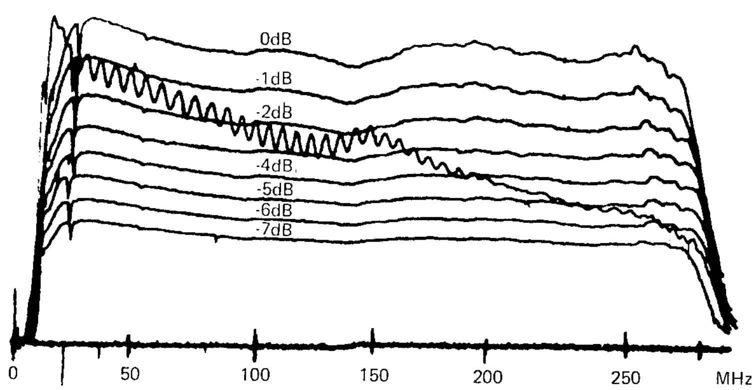
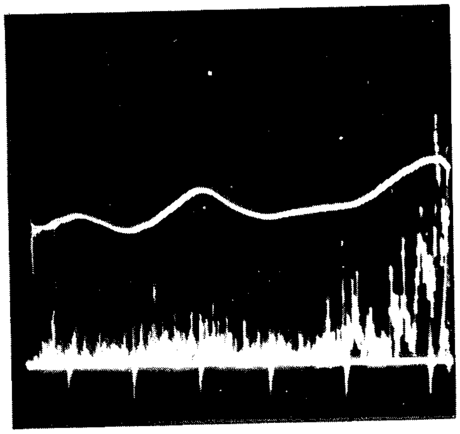
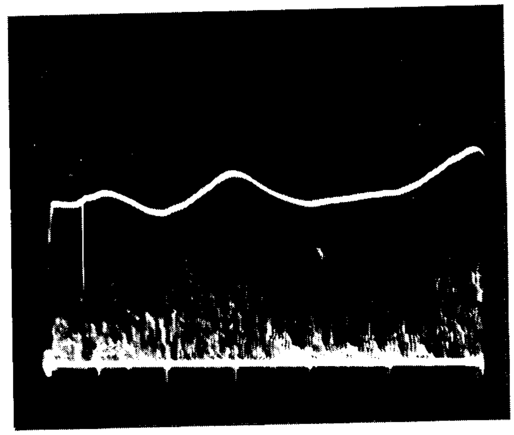


FIGURE 15
FIELD TESTING PROBLEM DUE TO NECESSITY TO USE LONG LEADS (50 FT. LONG RG-59) FROM SRL TEST SET TO BRIDGE
Shown is Measuring Circuit Attenuation Calibration
Note: Slope caused by attenuation of leads.



A. Reference level 39.2 dB Spike at 40 MHz



B. Reference level 39.8 dB Spike at 40 MHz

FIGURE 16

10-300 MHz SRL OF .412" FUSED DISC COAXIAL.
A = BEFORE INSTALLATION. B = AFTER INSTALLATION. LENGTH 1068 FT.

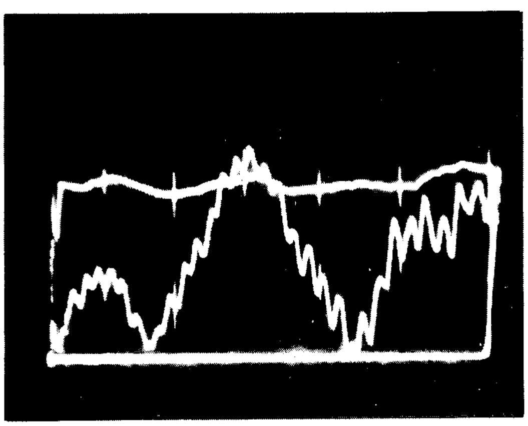
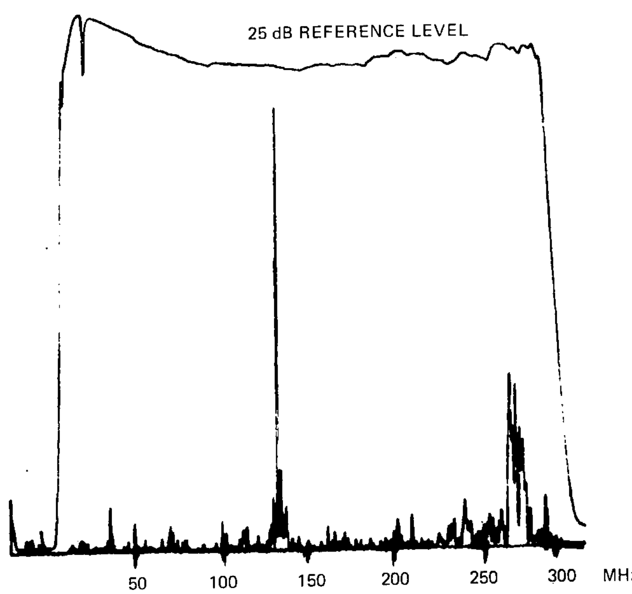


FIGURE 17

10-300 MHz SRL OF .412" FUSED DISC COAXIAL
WITH FAULT. REFERENCE LEVEL 20 dB.

FIGURE 18



10-300 MHz SRL OF .412" FUSED DISC COAXIAL
IN 4-TUBE COMPOSITE CABLE
NOTE: SRL spike and its harmonic due to cabling lay.

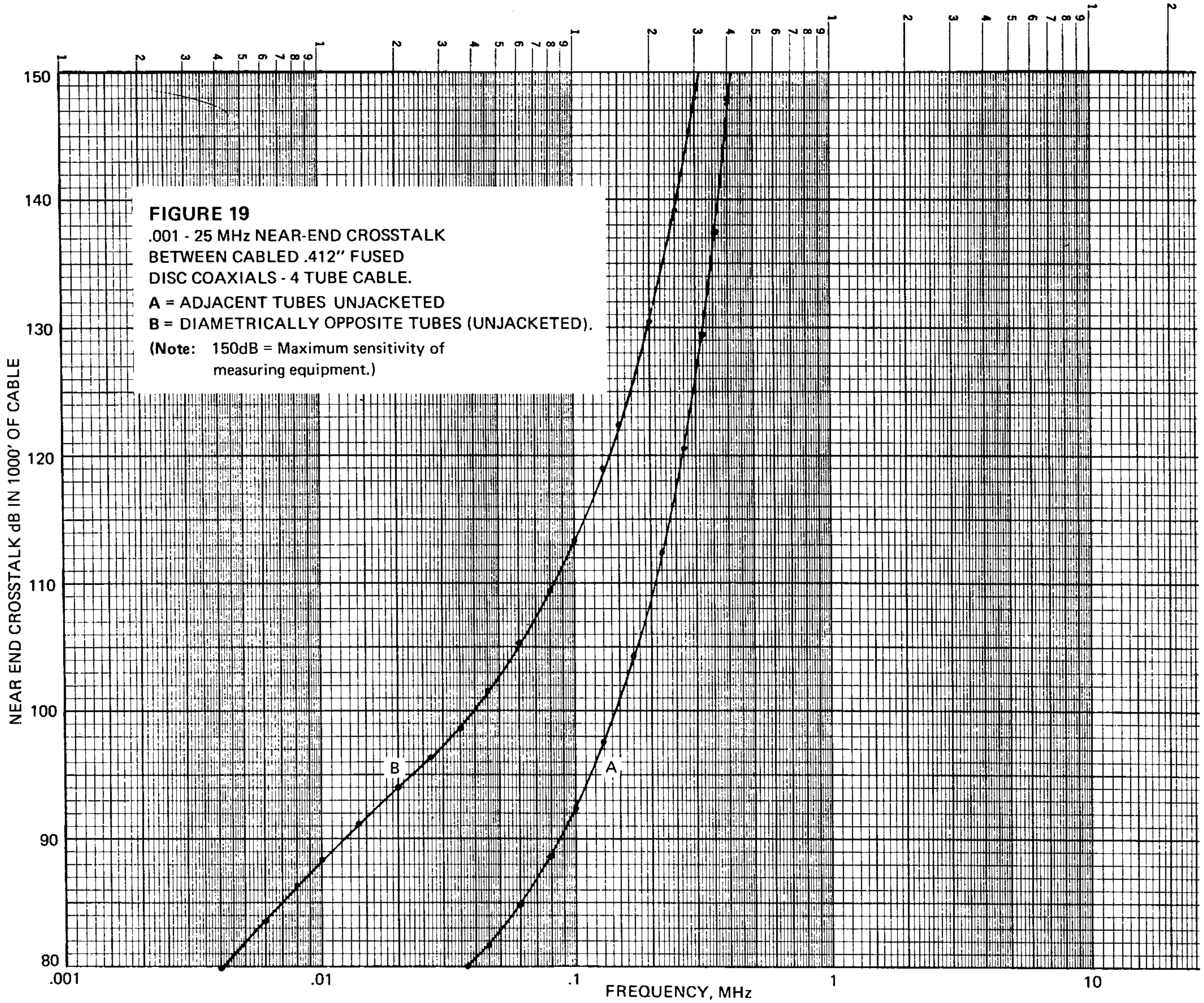


FIGURE 19
.001 - 25 MHz NEAR-END CROSSTALK BETWEEN CABLED .412" FUSED DISC COAXIALS - 4 TUBE CABLE.
A = ADJACENT TUBES UNJACKETED
B = DIAMETRICALLY OPPOSITE TUBES (UNJACKETED).
(**Note:** 150dB = Maximum sensitivity of measuring equipment.)

APPENDIX

The optimum thickness of the outer conductor for minimum resistance is given by the following relationship:

$$\frac{D_o - D}{2} = 3.12 \sqrt{\frac{\rho}{\mu f}} \tag{1}$$

The high frequency attenuation relationship in terms of dimensions and physical characteristics of materials is:

$$\alpha_t = \alpha_C + \alpha_G$$

$$\alpha_t = \frac{\sqrt{f\epsilon}\left[\frac{a}{d} + \frac{b}{D}\right]}{31.5 \log_{10} \frac{D}{d}} + 27.7 f \sqrt{\epsilon} \tan \delta \tag{2}$$

Since α_G is independent of dimensions, the derivative of α_t with respect to d becomes

$$\frac{d\alpha_t}{dd} = \frac{31.5\,(0.4343 \quad \ln D/d) \left(-\sqrt{f\epsilon}\right) \frac{a}{d^2} - \frac{\sqrt{f\epsilon}\left(\frac{a}{d} + \frac{b}{D}\right) 31.5\,(0.4343) \left(-\frac{D}{d^2}\right)}{D/d}}{[(31.5)\,(0.4343 \ln D/d)]^2} + 0$$

Setting $\frac{d\alpha_t}{dd} = 0$ gives the condition for minimum attenuation

$$\frac{D}{d}\left(\ln\ D/d - 1\right) = \sqrt{\frac{\mu_D\ \rho_D}{\mu_d\ \rho_d}} \tag{3}$$

The characteristic impedance at high frequencies can be expressed as:

$$Z = \frac{138.06 \log_{10} \frac{D}{d}}{\sqrt{\epsilon}} \tag{4}$$

The dielectric constant of a non homogeneous medium can be determined from the following:

$$\epsilon = \epsilon_a \frac{S-W}{S} + \epsilon_m \frac{W}{S} \tag{5}$$

and the dissipation factor from:

$$\tan \delta = \frac{W}{S} \frac{\epsilon_m}{\epsilon} \tan \delta_m \tag{6}$$

It is convenient to express the surface transfer impedance $Z_{\alpha\beta}$ as a function of K

$$Z_{\alpha\beta} = \mathcal{F}(K)$$

where

$$K = \sqrt{\mu\,\rho} \quad e^{-\alpha_s t} \tag{7}$$

and $\alpha_s = 0.505 \sqrt{\frac{\mu f}{\rho}}$ (8)

The expression for potential gradient in a perfect coaxial structure is:

$$g_x = \frac{E}{x \ln R/r} \tag{9}$$

and the maximum gradient at the surface of the center conductor is:

$$g_r = \frac{E}{r \ln R/r} \tag{10}$$

Taking the derivative of g_r with respect to r

$$\frac{dg_r}{dr} = \frac{-E\left[r \frac{r}{R}\left(-\frac{R}{r^2}\right) + \ln R/r\right]}{\left[r \ln R/r\right]^2}$$

and setting

$$\frac{dg_r}{dr} = 0$$

$$\ln R/r = 1$$

and $\frac{R}{r} = \frac{D}{d} = e = 2.718$, a condition for optimum diameter ratio from the point of view of discharge. (11)

The discharge potential expressed in practical terms is:

$$E = 31\, k_p\, r \ln R/r \tag{12}$$

In the above equation, the maximum gradient was assumed to be 31 kV-dc per centimeter for air at atmospheric pressure.

The torsional twist per cabling lay can be determined from the following relationship:

$$T = 360 - 4 \tan^{-1}\left(\frac{L}{2\,D_x}\right) \tag{13a}$$

for a floating carriage (planetary) cabler

and $$T = 4 \tan^{-1}\left(\frac{L}{2\,D_x}\right) \tag{13b}$$

for a fixed carriage (rigid-frame) cabler

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Mr. J. A. Olszewski received the Baccalaureate in Electrical Engineering at Loughborough College of Technology in Leicester, England and has done graduate work at the Polytechnic Institute of Brooklyn, N. Y. Prior to joining General Cable Corporation, Bayonne, N. J. in 1955, he was an electrical engineer in the development laboratories of Joseph Lucas, Ltd. in Birmingham, England. He is presently Senior Engineer in the General Cable Research Center. His special field is telephone and coaxial wires and cables.

Mr. H. Lubars received the B.S. degree in Mathematics from Waynesburg College, Waynesburg, Pa. in 1950 and the M.S. degree in Electrical Engineering from Newark College of Engineering, Newark, N. J., in 1962. He has been with General Cable Corporation since 1957 and is presently Senior Engineer in the Applications Engineering Department of the Communications Products Operation.

A NEW COAXIAL CABLE FOR PCM SYSTEMS

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Société Anonyme de Télécommunications
(S.A.T.)
Paris - France.

SUMMARY

Taking advantage of less stringent crosstalk requirements needed for PCM transmission a new so called "digital" coaxial pair was designed without the usual steel tapes protection.

The new technology makes it possible to manufacture in the same operation at least 4 coaxial pairs and to strand them in order to form a 4 pair unit similar to a star-quad construction.

Results obtained on an experimental link are presented and discussed.

INTRODUCTION

A few years ago, an extensive study program was undertaken by the French P.T.T. Administration in order to investigate economical and technical aspects of various PCM transmission systems over balanced and coaxial cables.

Among the numerous possible solutions a high speed 106 megabits per second 1440 channel PCM system was taken into consideration.

As far as the transmission characteristics of the line are concerned, the tentative figures were as follows :

- Spacing between regenerative repeaters .... 1.5 km
- Corresponding cable attenuation at 100 MHz .... 80 dB
- Near-end crosstalk ....> 40 dB
- Error rate per regenerative repeater .... 10^{-10}

The standardized 1.2/4.4 mm balloon insulated coaxial pair extensively used in French Telecommunication network for 1260 channel (and in the near future for 2700 channel) system has approximately the required high frequency attenuation and therefore it was decided to keep the same dimensions and the same insulation as for the normal 1.2/4.4 mm small coaxial tube.

But in some respects, the standardized small coaxial tube presents a very high level of performances which is not needed for PCM transmission.

Such is the case for crosstalk characteristics : the C.C.I.T.T. (*) recommended value is 95 dB for far-end crosstalk signal-to-noise ratio through the transmission band starting at 60 kHz for 3 km repeater sections. This high figure is met by using a rather thick outer conductor (0.15 mm in France and 0.18 mm in some other countries) and two steel tapes providing the electromagnetic shielding. In practice the steel tapes are either 0.10 mm thick plain steel tapes or 0.09 mm thick copper plated steel tapes, the latter being the solution adopted in France.

It soon became apparent that the less stringent crosstalk requirements of PCM systems may lead to a simpler and more economical design of the coaxial tube, namely reducing the thickness of the outer conductor and merely removing the steel tapes which are normally wound on the tube in helicoidal fashion.

But apart from their shielding effect the steel tapes hold the outer copper conductor in place and contribute to the mechanical stability of the coaxial pair.

In order to ensure satisfactory mechanical characteristics of the coaxial tube, even non covered with steel tapes, a new technology was developed.

(*) C.C.I.T.T. : The International Telegraph and Telephone Consultative Committee.

It has been found that if the coaxial pairs with overlapping outer conductor are assembled with a suitable twist, a bundle of coaxial pairs is obtained, after stranding, where the outer conductors are kept in place by the mutual pressure between the stranded pairs. The "unit", when comprising at least 4 coaxial tubes, exhibits sufficient mechanical strength to withstand the usual subsequent operations such as assembling several units into a larger size cable, lead covering, aluminum or steel welded sheathing, etc.. without the coaxial pairs suffering any cracking or opening.

We shall now describe the specification of such a "digital" coaxial pair as well as the different steps in the manufacturing process.

The comparison of construction between the 1.2/4.4 mm C.C.I.T.T. coaxial pair and the 1.2/4.4 mm digital coaxial pair is shown in fig. 1.

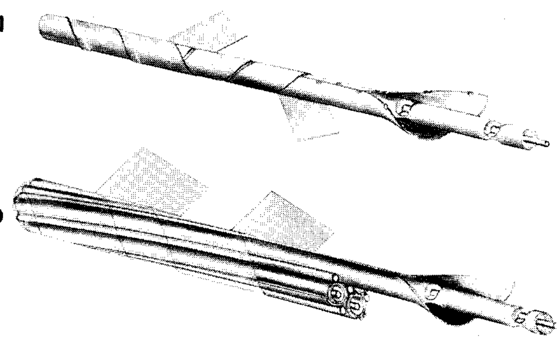

Fig. 1- Comparison between the 1.2/4.4 mm C.C.I.T.T. coaxial pair (a) and the 1.2/4.4 mm digital coaxial pair (b) configuration.

SPECIFICATION

- Inner conductor

  Copper wire 1.18 mm ± 5 μ

- Insulation

  "Balloon" type insulation (ref. 1)
  Weight : 4.5 g/m
  Permittivity : 1.18
  Diameter over insulation : 4.4 mm

- Outer conductor : copper tape 0.10 mm thick ± 6 μ

As already noted, there are no steel tapes or bindings over the individual coaxial tube.

MANUFACTURING PROCESS

INSULATION

- The inner conductor is insulated in a prior operation on a balloon extrusion line which has been frequently described in the technical litterature (ref. 2, 3).

TAPING AND UNIT STRANDING MACHINE

- Four coaxial pairs are produced simultaneously and stranded together in line in order to form a 4 pair unit similar to a star quad construction (ref. 4).

Fig. 2 is a photograph of the prototype machine used for production of such a 4 pair unit and a close-up view of the forming head is shown in fig. 3.

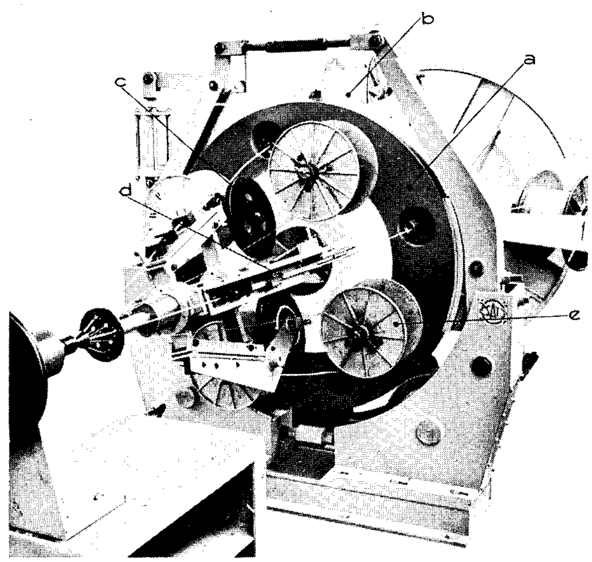

Fig. 2- Simultaneous taping and unit stranding machine for the manufacture of a four digital coaxial 1.2/4.4 mm pair unit.

a - Rotating cage.
b - Pay-off reels for the insulated inner conductors.
c - Copper tape supply pads.
d - Forming heads for the outer conductors.
e - Fillers supply reels.

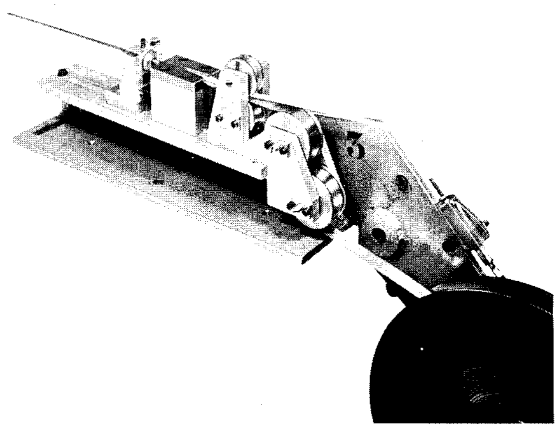

Fig. 3- Close-up view of the forming head.

The main part of the machine is the rotating cage of a conventional laying-up machine with four pay-off reels supplying the insulated inner conductor.

Four copper tape supply reels are mounted on the cage plate as well as the four forming heads. The copper strips are fed from the supply reels through progressive shaping dies and form around the central insulated wire the outer conductor of the coaxial pair. The spaces in the center of, and between the coaxial pairs are occupied by intersticial coloured polyethylene fillers in order to obtain a better geometry of the unit and to allow the identification of the coaxial pairs. The four coaxial tubes are stranded without detorsion and the resulting twist applies very tightly the outer conductor over the insulated wire and provides an accurate control of the diameter.

As for the central insulated wires, it is preferable, on the contrary, to let the supply reels rotate in a planetary way in order to feed the central insulated conductor with complete detorsion.

The unit, comprising 4 coaxial tubes and 5 fillers, is pulled by a capstan through a stranding die and, after being covered with two binding plastic tapes, is received on a conventional take-up stand.

At this stage of manufacturing, the unit exhibits a good mechanical stability and further steps can be undertaken without damaging the coaxial pairs.

STRANDING

In order to form a large size cable, a certain number of primary units are stranded together. We have already manufactured, using a planetary strander, 28, 24 and 16 coaxial pair cables (corresponding to 7, 6 and 4 primary units) but the production of still larger cables has also been considered.

Code-coloured polyethylene tubular fillers occupy the free spaces between units, permitting the identification of the units and contributing to the geometrical stability of the cable.

SHEATHING

Different kinds of outer protection were equally successeful :

- lead sheath with or without plastic jacket

- aluminum welded and corrugated sheath with polyethylene jacket

- steel welded and corrugated sheath with polyethylene jacket (experimental lengths only).

CROSSTALK CHARACTERISTICS AND THEIR IMPROVEMENT

Coming back to the problem of crosstalk which was briefly mentioned above, in our unit type cable construction two aspects have to be considered :

- crosstalk within the unit between adjacent or opposite coaxial pairs

- crosstalk between pairs which belong to different units (i. e. "crosstalk between units").

The near-end crosstalk attenuation (NEXT) versus frequency for 28 coaxial pair (7 units) cable is shown in fig. 4.

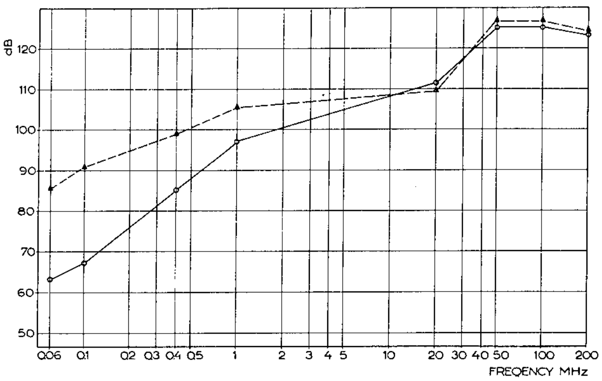

Fig. 4- Near-end crosstalk attenuation (Envelope of minimum values)
28 coaxial pair (7 units) cable
Length = 500 m

o——— *All combinations within the unit*

Δ----- *All combinations between units.*

The far-end crosstalk signal-to-noise ratio (FEXT) versus frequency for the same type of cable is shown in fig. 5.

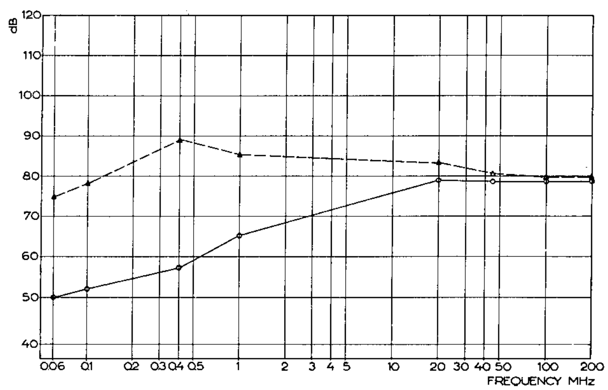

Fig. 5- Far-end crosstalk signal-to-noise ratio (Envelope of minimum values)
28 coaxial pair (7 units) cable
Length = 500 m

o——— *All combinations within the unit*

Δ----- *All combinations between units.*

For comparison, the NEXT in our currently produced cables containing several 1.2/4.4 mm coaxial C.C.I.T.T. type pairs, is better than 126 dB (minimum values at 60 kHz measured on 460 m factory lengths)

On the other hand, the NEXT is much more critical than the FEXT and we can take advantage of the unit type construction by specializing all four coaxial tubes of any given unit for transmission in the same direction. Therefore, the significant crosstalk within the unit is the FEXT ; the NEXT is to be taken into consideration only between different units.

If necessary, the latter can be easily improved by wrapping around the unit a metallic tape acting as a shield. A very effective result was obtained with a copper plated steel tape 0.05 mm thick.

Fig. 6 concerns the NEXT for 16 coaxial pair cable (2 units without steel tapes + 2 units with steel tapes) and shows the improvement of the crosstalk level due to the shield around the unit.

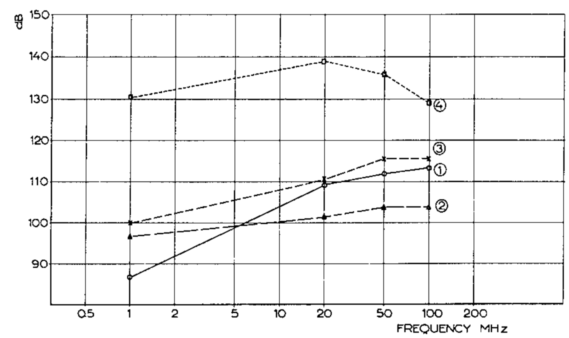

Fig. 6- Near-end crosstalk attenuation (Envelope of minimum values)
28 coaxial pair cable (2 units with steel tapes + 2 units without steel tapes)
Length = 250 m

(1) o——— *All combinations within the unit without steel tapes*

(2) Δ——— *All combinations within the unit with steel tapes*

(3) x---- *All combinations between units without steel tapes*

(4) □---- *All combinations between units with steel tapes.*

Further, and assuming that a higher crosstalk quality level within the unit is needed in some particular cases, this aim can be achieved by using, for the return conductor, a composite tape such as copper/steel/copper instead of a plain copper tape.

FIELD TRIALS OF DIGITAL COAXIAL PAIRS

In order to assess the mechanical behaviour of this new type of coaxial cable during manufacturing, laying and splicing as well as the electrical properties from the point of view of PCM transmission characteristics, a digital coaxial pair link was installed in SAT Experimental Cable Center in Lannion (Brittany). Lannion is the home of very important CNET (*) Research Laboratories and is situated near Pleumeur Bodou, the French Space Communication Ground Station.

The layout of the line is shown in Fig. 7.

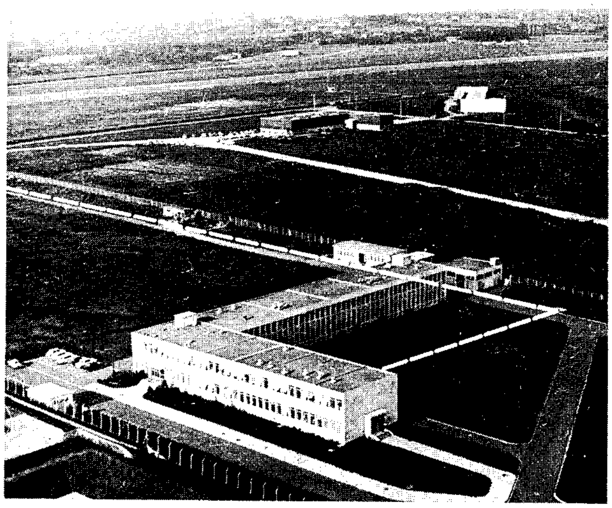

Fig. 7- Layout of the line in SAT Experimental Cable Center in Lannion.

The line length is 1.5 km consisting of six cable sections, each 250 m long and made according to the following design :

- one twenty four coaxial pair cable (3 units with and 3 units without steel tapes) (see photograph fig. 8).
- two twenty four coaxial pair cables(6 units without steel tapes).
- one sixteen coaxial pair cable (2 units with and 2 units without steel tapes).
- two sixteen coaxial pair cables (4 units without steel tapes).

(*) CNET : Centre National d'Etudes des Télécommunications.

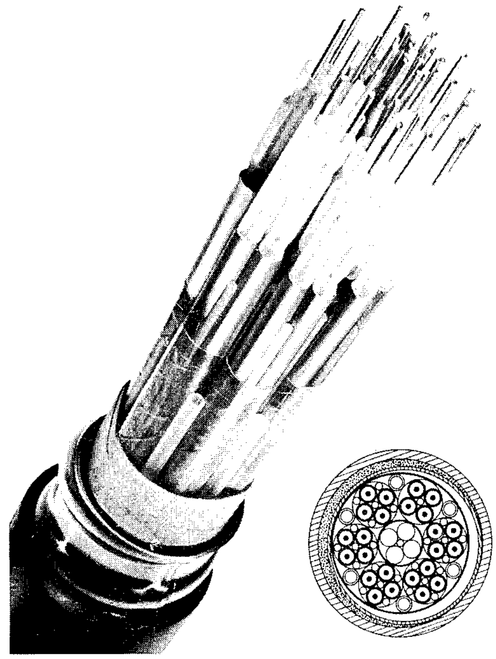

Fig. 8- Twenty four coaxial pair cable with aluminum sheath and polyethylene jacket.

The total length of coaxial pairs is therefore 30 km. The spacing between regenerative repeaters being 1.5 km, the transmission loop represents 20 sections in one direction or 10 sections in the case of two-directional transmission.

Geographically, there are 3 repeater points, two of them are located at the Cable Transmission Laboratory and the third in a specially built underground chamber. Each repeater case, made of brass, can house 24 regenerative repeaters.

The arrangement described above proved to be quite versatile and enabled us to carry out numerous tests. For instance we studied the shielding effect of additional steel tapes according to the position of the shielded units in the regenerative section. More generally we have collected valuable data on the intrinsic cable parameters.

The main objective in designing this experimental 30 km long coaxial line was the field testing of a 106 megabits per second PCM system. In addition, some other investigations were undertaken ; we shall mention in particular a digital color TV signal transmission.

106 MEGABITS PER SECOND PCM SYSTEM.

Starting with a group of 30 channels (modulation speed 2.048 megabits per second), we built up the 1440 channel system in the following steps :

30 channels x 3 = 90 channels

90 channels x 4 = 360 channels

360 channels x 4 = 1440 channels

We shall see later that this capacity is also suitable for one channel color TV digital transmission.

The signal transmitted over the line is generated by the terminal equipment simulating pseudo-random messages with a modulation speed of 106 megabits per second (9.4 ns interval between two consecutive pulses).

At the receiving end of the 30 km link, an error detector device with automatic recorder and counter indicates the number of faults occuring during the transmission : either absence of a significant information pulse or, on the contrary, fortuitous appearance of an irrelevant pulse.

After two years of operation, the rate of errors is better than 10^{-10} per regenerative repeater.

Assuming a link of 1500 km total length consisting of 1000 regenerative repeaters, the estimated rate of errors would be better than 10^{-7}, which is perfectly acceptable.

Two other essential parts of the system were also tested :

- the power feeding of the regenerative repeaters (12 volts DC 300 mA) proved to be highly reliable ; the equipment is similar to the one widely used in the French coaxial cable network.

- the remote identification of a faulty regenerative repeater is performed from the terminal stations, using an original stel-by-step method ; its effectiveness was confirmed by creating artificially different kinds of faults and checking the location of the regenerative repeater involved.

It is important to point out that all these auxiliary functions (remote control, power feeding, fault signalling ...) do not require special additional circuits in the cable but instead make use of the digital coaxial tube itself.

CODED COLOUR TV SIGNAL TRANSMISSION

A modulation speed of 106 megabits per second is theoretically sufficient for a good quality transmission of a color TV signal with 625 line resolution. The purpose of the experimentation carried out in our Lannion Cable Center under CNET supervision was to demonstrate this possibility and to study the influence of the rate of error on the quality of the received image (ref. 5).

The method of encoding is a version of differential modulation called "ΣΔ" (sigma-delta) system (ref. 6 and 7). The "ΣΔ" encoder delivers a stream of pulses modulated in density proportionally to the instant amplitude of the video signal. The output binary signal passes through a transcoder and becomes a trinary coded signal which is transmitted over the line. At the receiving end are located the corresponding decoders which finally restore the video signal. The block diagram is shown in fig. 9.

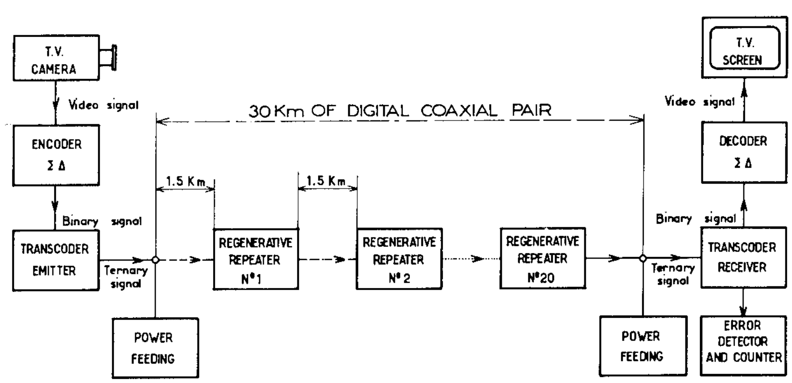

Fig. 9- Block diagram of the experimental link for TV transmission.

One of the built-in features of the installation was that it enabled us to degrade voluntarily the characteristics of the line by injecting a certain amount of noise correlated with the video signal in order to increase the rate of errors.

It was experimentally confirmed that the theoretical figure of 10^{-6} is absolutely negligible compared with the quantizing noise of the "$\Sigma\Delta$" system. Even a 10^{-5} error rate does not permit to distinguish between the transmitted picture and the original picture. It seems that a 10^{-4} error rate causes a slight deterioration of the picture but a 10^{-3} figure is certainly not tolerable.

CONCLUSION

The Lannion experimental line was rather oriented towards testing of the "digital" coaxial pair as a transmission medium for high speed PCM systems ; the associated regenerative repeater was designed in view to equip a sufficient length of coaxial pair for a valid experimentation, and this purpose was achieved to our complete satisfaction.

The technology available at the time (early 1969) for line equipment is now superseded by latest developments in the field of integrated circuits, and the equipment involved in the most recent projects of the French Administration takes full advantage of this technical progress.

Priority is now given to a 50 megabits per second 720 channel system with regenerative repeater spacing of 2 km, which is compatible with the C.C.I.T.T. recommended 12 MHz analog system. A commercial link is planned for 1973 between Paris and Meaux (about 50 km).

As a next step, there is also under consideration the possibility to employ a multilevel encoding method instead of a ternary code, therefore extending the speed up to 100 megabits per second or more, at least doubling the channel capacity and keeping the same 2 km regenerator spacing.

May we add that a 25 megabits per second 360 channel PCM system already developed for microwave transmission, can easily be adapted to transmission over the digital coaxial pair. The regenerative repeater spacing would be in this case 3 km, and therefore compatible with the analog C.C.I.T.T. recommended 6 MHz system.

ACKNOWLEDGMENTS

The authors wish to thank the members of the "CNET" for the interest taken in this research project. Their guidance and support were greatly appreciated.

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BROAD-BAND LEAKY COAXIAL CABLE WITH SMALL SIZE COAXIAL CABLES IN IT'S INNER CONDUCTOR

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K. MIKOSHIBA**, T. HANAOKA**

ABSTRUCT

The leaky coaxial cables are effective transmission media not only to a place where the radio waves are unable to penetrate, but also to a place where communication services are needed along the lines such as railroad for high speed train and highway.

The leaky coaxial cable which is able to integrate the vehicular communications and the point-to-point communications along the railroad is developing in Japan. In this paper, the performances of the such integrated leaky coaxial cable are described.

1. INTRODUCTION

Recently, leaky coaxial cables (LCX) are planning to install in order to get stable vehicular communications in place where the radio waves are unable to penetrate.(1) These lines will be effective transmission media in place where communication services are needed along the lines such as railroad and highway. In order to realize the linear communication system,(2) mentioned above, using the LCX, the cable with wide-band transmission and radiation performances, and the another cables for the point-to-point communications are needed simultaneously. Then, by a newly developed broad-band LCX with the small size coaxial cables in it's inner conductor, as shown in Fig. 1, the linear communications integrating the vehicular and point-to-point communications may be made possible. Japanese National Railways Co. is developing such communication systems for High-Speed Train.

This integrated LCX has many technical problems to be developed, for examples, wide-band technique to get uniformity of the leaked waves along the LCX over the frequency range from 150 MHz band to 400 MHz band, connecting system to separate the inner cables from the integrated LCX, installation method not to degrade the characteristics of the LCX even in trough installation on the earth's surface, and various kinds of electromagnetic interference which are transformed into noise in the cables. Except the interference on the communication cables the other technical problems have never been investigated because these problems have not been needed in the past.

The purpose of this paper is to present a possibility of the LCX which is able to integrate the vehicular communications and the point-to-point communications.

2. DESCRIPTION OF THE CABLE

The LCX described here is mainly provided 400 MHz band vehicular communications. Therefor, the size of the coaxial cable may be larger than usual coaxial cables and there is space where another cables for the point-to-point communications are able to be fabricated in the inner conductor of LCX. The LCX with another cables in it's inner conductor may be called the integrated LCX because it makes possible to integrate the vehicular and point-to-point communications. The cost of the integrated LCX may be lower than total cost of the LCX and the another cables for the point-to-point communications. A physical structure and a photograph of a kind of the integrated LCX are shown in Fig. 1. This integrated LCX has two small size coaxial cables and a quad cable with shield layer in LCX's inner conductor.

In order to provide various kinds of stable communication services for vehiculars the LCX must have radiation performances over wide-band frequency, and moreover the good uniformity of the leaked waves along the LCX must be satisfied over wide-band frequency. By satisfying the radiation condition and avoiding the interference of the radiation waves the good uniform distribution of the leaked waves is able to be achieved.(1) But, it needs the special slot arrangement to get the good uniformity of the leaked waves at frequency from 150 MHz band to 400 MHz band. The integrated LCX system consists of the LCX with 4 different values of coupling loss,(1) and the electrical performances of the integrated LCX base on Japanese National Railways requirement, because it is necessary to reduce the difference between the maximum and minimum field strength over long distance.

3. ELECTRICAL PERFORMANCES

Electrical performances which are required transmission line may be usually determined by concrete communication system adapted the transmission line. The integrated LCX is separated two parts, that is, the transmission line for coaxial carrier and the transmission line for wireless circuit.

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**K. MIKOSHIBA, T. HANAOKA are with Hitachi Cable, Ltd.

IF repeater system which is going to be operated at New Sanyo Line is investigated as one method of repeater system for wireless circuit using the LCX. The frequency for the IF repeater system will be between 10 MHz and 30 MHz, and IF signal transmits in the LCX. Three signal, that is, IF, 150 MHz band and 400 MHz band signal, therefor, transmit in the LCX.

A. Electrical performances of the small size coaxial cables in the LCX's inner conductor

The inner cables of the LCX consist of two small size coaxial cables (1.2/4.4mm) and a quad cable. These 1.2/4.4mm coaxial cables base on the C.C.I.T.T. recommendation, and there are not technical problems in this field.

Construction over these small size coaxial cables is so complicated as shown in Fig. 1 that process of manufacture of the LCX over the 1.2/4.4mm coaxial cables is utmost important in order for the 1.2/4.4mm coaxial cable to meet the specification of impedance regularity.

B. Electrical performances of the LCX

IF frequency band

The coaxial cable as shown in Fig. 1 has low-loss characteristics at IF band (10 MHz ~ 30 MHz), and then it is investigated as transmission line for repeater system of wireless circuit. The LCX is very different from ordinary coaxial cables because the LCX has the periodic slot on outer conductor.

Communication cable may be exposed to various kinds of electromagnetic interference, then this interference is transformed into noise in communication circuit. In a cylindrical tube having a longitudinal gap or a shields which have a longitudinal seam it is well known interference increases with frequency.(3) (4) Noise into which interference is transformed, therefor, is one of serious problems of IF repeater system in the linear communication using the LCX.
The shielding parameter on the interference is known as the surface transfer impedance. Measured values of the surface transfer impedance of the LCX with the longest slot are shown in Fig. 2. This performance of the surface transfer impedance of the LCX has same tendency to that of coaxial cable with braided outer conductor.

150, 400 MHz band

The integrated LCX was mainly designed vehicular communications using 400 MHz band, and mover was added the good uniformity of the leaked waves at 150 MHz band. The linear communication system using the LCX disscussed here consists of the LCX with 4 different values of coupling loss. These LCX have 50 ohms as characteristic impedance, and the electrical performances such as attenuation and coupling loss are shown in Table 1.

At measurement of the coupling loss as shown in Table 1 the LCX is laid on a concrete floor, and the distance between the LCX and dipole antenna keeps 1.5 meters high. The electrical performances of one type of the LCX laid on a concrete floor are shown in Fig. 3. The LCX reported in this paper has wide-band (from about 100 MHz to around 500 MHz) transmission and radiation performance as shown in Fig. 3 except at some frequency which is determined by spacing of slots measured by wavelength in the LCX.

There are many problems to be investigated in trough installation of the LCX on the earth's surface. It is clear that the performances of the LCX are not degraded when the LCX is just laid on a concrete floor. However, the LCX, as shown in Fig. 1, has not any armor structure and the LCX laid just on a concrete floor is lacking in the reliability as the transmission line. At the installation of the LCX on the earth's surface the LCX has to be protected by trough or duct. Since electromagnetic energy is stored in the vicinity of the LCX, the transmission performances, especially, attenuation, are strongly affected by kind of material of trough or duct, and by dimension of those. There is no room in this paper to discuss the relations between transmission performances and the above factors of trough or duct in the detail. In order to achieve field test of the integrated LCX planned by Japanese National Railways, a kind of baked trough (For example, like pottery) was used after investigating several kinds of trough. The performances of the LCX after the trough installation are shown in Table 1 with those of the LCX laid on a concrete floor, and in Fig. 3 as function of frequency. The uniformity of the coupling loss along the each LCX becomes slightly bad after the trough installation as shown in Fig. 3, and the difference of 50% value of the coupling loss between the LCX laid on a concrete floor and the LCX installed in the trough is less than 2 dB. Except 145, 146 type LCX, attenuation is slightly affected by material of trough or duct.

The above discussion on the coupling loss is mainly the uniformity along the LCX. However, thinking communication services along the lines such as railroads and highways the regions where vehicular communications using the LCX are able to be served may be determined by radiation performance toward perpendicular to the LCX-axis. The coupling loss-distance performances are shown in Fig. 4 at 150 MHz and 450 MHz. Circular component and axial component of electrical field of the LCX become radiation waves, and radial component is inductive field. Fig. 4 explains these relationship. From this result of Fig. 4 service area of the LCX is wider and the LCX system may be able to be applied highway's linear communications.

4. CONNECTING SYSTEM

Connector which separates the inner small size coaxial cables from the integrated LCX may be a key of the possibility of the LCX. Separating the inner cables it is required not to degrade the transmission performances of the LCX at the frequencies of IF band, 150 MHz band and 400 MHz band. Therefore, the connector for the integrated LCX must have low-insertion loss and low V.S.W.R. Separation method described in this paper uses principally T-junction. One line of T-junction becomes the LCX circuit and the inner small size coaxial cables are separated from another line of T-junction. Travelling signal in the LCX at only one higher frequency band, the connector is easily realized by T-stab and the separation of the inner cables is achieved by using one shorted line of T-stab.

Travelling signal at lower frequency at which it is difficult to apply the distribution circuit technique T-stab with shorted line is not available, but T-junction is useful for the connector as shown principal concept in Fig. 5. The chocke acts to stop the outer-wall currents at higher frequency, but another method have to be obtained in order to stop the outer-wall currents at the lower frequency. The lower frequency means IF frequency band in this paper and ferrite cores are used. Insertion loss and return loss (equivalent to V.S.W.R.) of the connector are shown in Fig. 6.

There is another connecting method without separating the inner cables from the LCX. The connecting method which joints directly each cable may be important and may be suitable for just connecting the integrated LCXs, because the electrical performances may be improved, and moreover, the cost of this connecting method is cheaper than that of the other one discribed at the first part of this section. However, the connector separating the inner cables from the integrated LCX is most important at the repeater of the inner cables and also the LCX circuit.

The field trial of the integrated LCX has been done by Japanese National Railways. The route which was constructed by Hitachi Cable, Ltd. has consisted of 147, 146 and 145 type LCX as shown in Fig. 7. The connection of each type LCX has been done by the separation type connector as shown in Fig. 8. Fig. 9 shows a view of the field trial route and the trough installed the integrated LCX. According to the total transmission loss illustrated in Fig. 7 the total loss at IF band is large in comparison with that at 150 MHz band. Main reason of this result is that the electrical performances at IF band is not proper as shown in Fig. 6.

5. CONCLUSION

It became clear that the integrated LCX makes possible the integration of the vehicular and point-to-point communications by using only one cable. Putting the integrated LCX into practical use, the following problems should be investigated:

(1) Noise level into which interference is transformed, and transmission line for repeater system.

(2) Practical installation method as proper protector of the LCX.

(3) Improvement of the electrical performances of the connector for separation.

It would seem that there areas are still wide open to major improvements with more room for invention and development.

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TABLE I. ELECTRICAL PERFORMANCES OF LCX

FREQUENCY / TYPE	ON A CONCREATE FLOOR				IN THE TROUGH			
	ATTENUATION (dB/km)		COUPLING LOSS (dB)		ATTENUATION (dB/km)		COUPLING LOSS (dB)	
	150 MHz	450 MHz	150MHz	450MHz	150MHz	450MHz	150MHz	450MHz
145	20.5	35	57.3	54.2	20	39	59.2	53.5
146	12	24	65.5	60.8	13	30	64.2	58.5
147	13	22	74.5	68.8	12	21	75.5	70.2
148	11	21	84.5	79.3	11	21	85	80.4

COUPLING LOSS IN THIS TABLE SHOWS 50 % VALUE

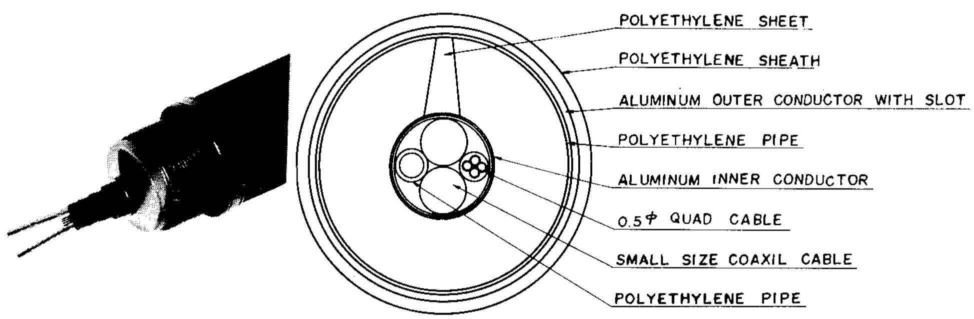


Fig. 1 PHYSICAL STRUCTURES OF THE LEAKY COAXIL CABLE WITH SMALL SIZE COAXIL CABLE

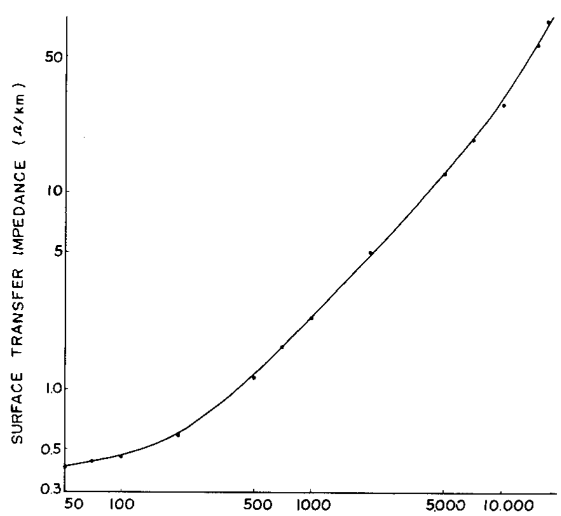


Fig. 2 MEASURED SURFACE TRANSFER IMPEDANCE FOR 145 TYPE LCX

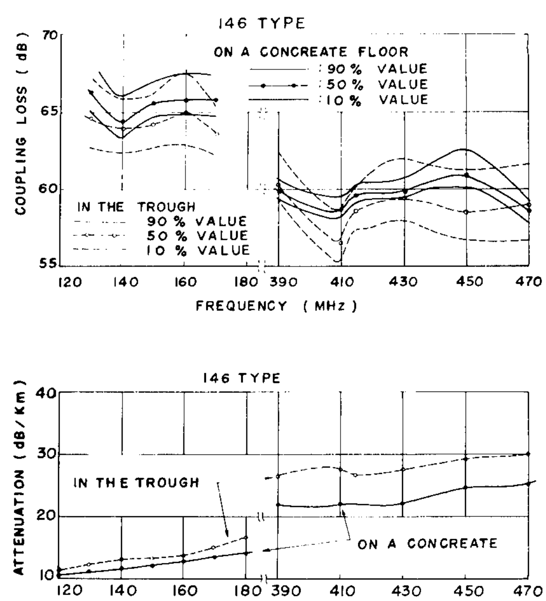


Fig. 3 THE ELECTRICAL PERFORMANCES OF 146 TYPE LCX LAID ON A CONCREATE FLOOR AND IN THE TROUGH

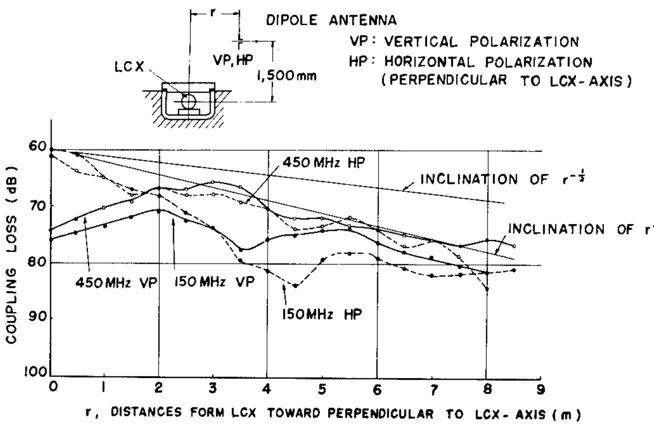


Fig. 4 COUPLING LOSS-DISTANCE PERFORMANCES

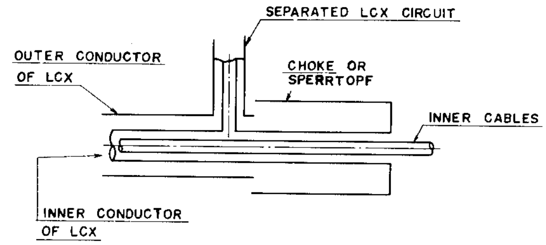


Fig. 5 PRINCIPAL CONCEPT OF CONNECTOR USING T JUNCTION

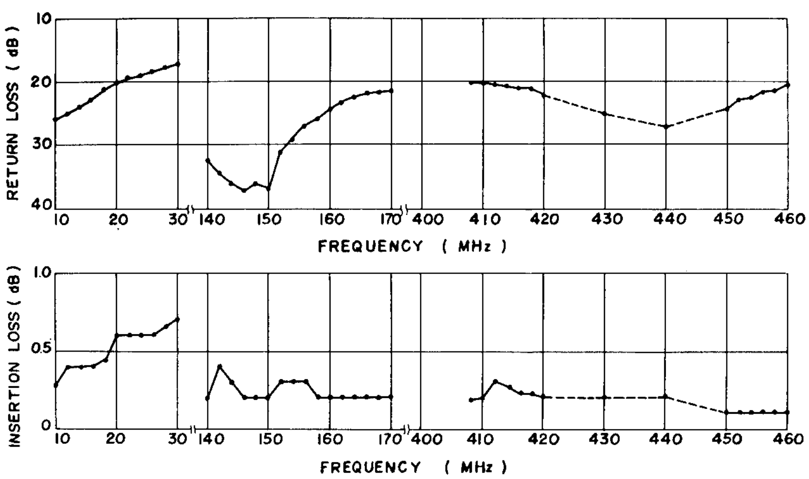


Fig. 6 ELECTRICAL PERFORMANCES OF CONNECTOR SEPARATING INNER CABLES

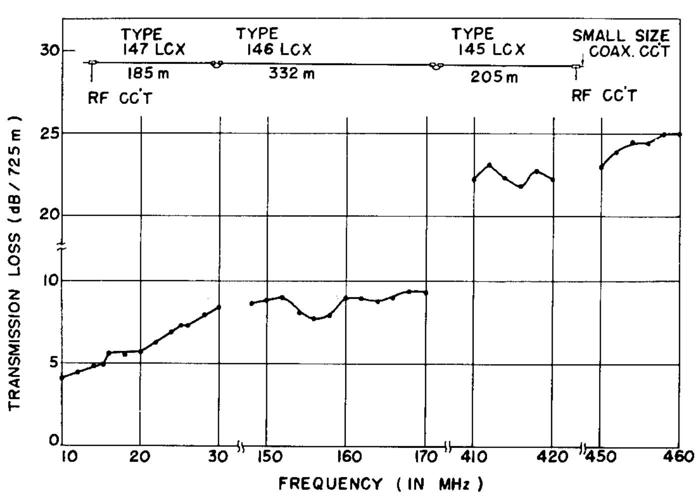


Fig. 7 CABLE ROUTE AND TOTAL TRANSMISSION LOSS OF LEAKY COAXIAL CABLE

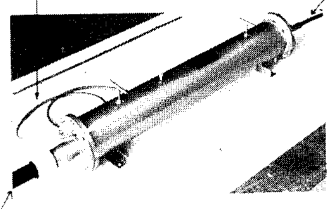


Fig. 8 CONNECTOR SEPARATING THE INNER CABLES FROM THE INTEGRATED LCX

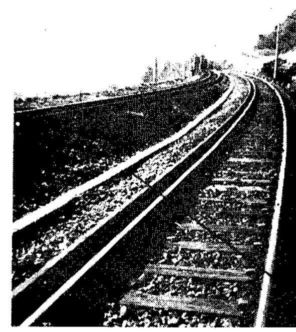
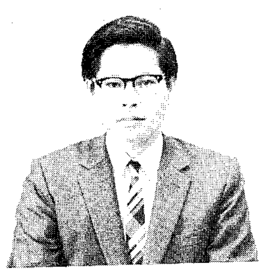


Fig. 9 THE INTEGRATED LCX INSTALLED BETWEEN RAILWAYS

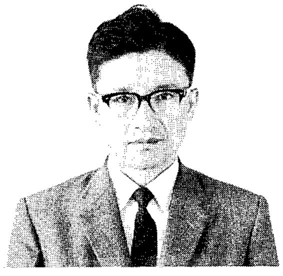


Koichi Mikoshiba was born in Matsumoto City, Japan on 1937. He received the B.E. and Ph.D. degrees in electrical engineering from Tohoku University, Sendai, Japan in 1957 and 1967, respectively.

In 1959, he joined Hitachi Cable, Ltd., Tokyo, Japan, where he has been a Research Member of the Research Lab. He has been engaged in the development of millimeter circular waveguides, UHF antenna systems for television broadcasting, and in the research and application of such nonconventional waveguides as surface-waveguide, leaky waveguide, beam waveguide and leaky coaxial cable system.

From 1968 to 1969 he was a Post Doctoral Fellow at the MRI of Polytechnic Institute of Brooklyn, N. Y.

Dr. Mikoshiba is a member of the Institute of Electronics and Communication Engineers of Japan, and I.E.E.E.



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In 1957, he joined Hitachi Cable, Ltd., where he has been engaged in the development of the communication Cables. He is now a Senior Engineer in The Communication Cable Design Section.

Mr. Hanaoke is a member of the Institute of Electronics and Communication Engineers of Japan.

DIELECTRIC PROPERTIES TESTING OF INSULATION ON WIRE/CABLE COMMON TO THE AEROSPACE INDUSTRY

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Abstract

This presentation reveals investigative, corrective, and control activities by McDonnell Aircraft Company in an effort to insure optimum integrity of wire/cable ultimately accepted from processors for use in Aerospace Products and, in general, the influence these efforts had in upgrading the quality of wire/cable concerning the Aerospace Industry.

Introduction

MCAIR Program Purpose Questioned

Although couched in varying types of phraseology the questions have often been asked, "Why is McDonnell Aircraft Company (MCAIR) expending so much effort and incurring so much expense to verify and assure the integrity of incoming bulk electric wire/cable?". "Isn't it the responsibility of wire manufacturers and processors to produce wire to definite specifications and to assure and certify that only that wire which meets these requirements is released to customers?" These questions were in some instances most delicately posed and answered with a comparable degree of tact. The answers to these questions are always, essentially, the same and merely tempered dependent upon whether the question emanated from MCAIR internal management or was on the basis of a supplier customer relationship.

An attempt will be made in this article to define the reasons why MCAIR engaged in such a comprehensive wire improvement and control program, including the thinking which dictated some of the courses pursued. Also discussed will be how the program was conducted, circumstances encountered, improvements and corrections instituted, preventive controls employed and the monitoring and control systems installed.

The program benefits which are believed to have accrued to MCAIR and those improvements considered to have resulted which are beneficial to organizations external to MCAIR will also be treated in some detail.

Other Companies Participate

In the interest of assuring a proper perspective when reading this paper, it is recommended that the reader remain aware of the fact that this endeavor was not an exclusive effort of MCAIR. Personnel of a number of companies and agencies participated and contributed through understanding, cooperation, technical advice and guidance, making equipment and facilities available, attendance and contributions in seminars, symposiums, meetings, etc.

Aerospace Industry Precepts Regarding Quality

The operating principles which govern the normal conduct of Aerospace Quality Assurance activities must be recognized to fully appreciate the factors which motivated this wire improvement program.

The most important consideration, which of course overrides all others, is concern for conditions which could potentially have an adverse affect on the welfare or safety of users/crewmen of Aerospace Products, and for the vehicle itself. There are, incidentally, almost unlimited applications of wiring in Aerospace Products; the failures of which could have a direct impact in this respect.

Granted! "the best thing to do about a discrepant item is to not make it". However, in the interest of reality and discarding the probability of total manufacturing perfection, discrepant articles should be detected and restricted to the manufacturer's or supplier's facilities.

In recognition of the possibility, and previous cases, of inadvertent supplier shipment of nonconforming articles, the Aerospace Manufacturer must be capable of detecting these items at the Receiving Inspection stages.

Compounding "Quality" Problems

Failure to detect nonconforming articles at either of the foregoing preliminary check points sets the stage for relatively increasing difficulties equatable to time elapsed, extent of progression of the item through assembly and installation operations, and the degree of dissemination of such items to end customers.

Detection of nonconformities in component articles at stages subsequent to release by a supplier also invokes penalties in the form of relative increases in delays, manhour expenditures, overall costs, and finally the associated stigma as attached by the end customer.

A principal objective of MCAIR when conducting this program has been to prevent a "fiasco" i.e., an incident wherein the entire production line is polluted as well as numerous

end items (aircraft, etc.) which have been delivered over an extended period of time and to various bases prior to discovery that discrepant components have been incorporated. Experiences with a limited number of such incidents is sufficient to convince any sensitive Quality Assurance Division of the wisdom of instituting preventive measures to avoid such experiences in the future, regardless of the preventive effort required.

MCAIR Commences Program

For some time prior to inception of the MCAIR Wire Improvement/Verification Program the subject type wire was, generally, accepted on the basis of Wire Processor's/Supplier's certifications. In April, 1969, it came to the attention of MCAIR Quality Engineering that as a result of a very limited footage of Teflon insulated wire being tested for dielectric properties, by use of the "tank type solution testing method", the wire tested was found to exhibit an inordinate number of insulation defects.

In immediate response to this alert, sample quantities from various wire lots were similarly tested and did indeed contain essentially the same types of discrepant conditions. Testing of these sample quantities revealed that failures were occurring at as low as 400 to 800 volts although per Mil Specification requirement the insulation should have been capable of withstanding 2200 volts for one minute. On the basis of this preliminary investigation, it was seriously suspected that MCAIR was in fact being subjected to excessive footages of nonconforming wire, and that a deeper study would be required to assess the true seriousness and extent of the problem. Subsequent investigations and studies confirmed these suspicions and also that the problem was common to various sources of supply and highly repetitious in nature. Fortunately, only a limited number of incidents, equipment malfunctions, etc., were positively traceable to this type of inferior wire/cable and no cases of major failures were assignable to this cause. The now apparent "industry wide" scope of the problem plus the unknown duration gave evidence of the impending difficulties which would be encountered in effecting necessary improvements and controls. During the course of preliminary studies, it was learned that in the past there had been several abortive attempts to gain a solution to the problems of detecting deficiencies and controlling the quality of incoming wire in general.

It was determined, at this time, that a very comprehensive program would be required and would be resolutely prosecuted through a successful conclusion. In order to accomplish this ambitious task it was, naturally, necessary to assure a "unified front". Therefore, an intensive coordination was commenced to assure that all MCAIR Divisions were in agreement as to the nature of the overall problem and the direction of the effort.

In addition to alignment of MCAIR internal forces it was necessary to enlist the participation of a number of other companies including raw materials manufacturers, conductor fabricators, wire processors, and equipment manufacturers. The response by all participating personnel was proven to be most necessary, extremely gratifying, and surely a fine cooperative effort recognized by all involved. The conduct of this program was very unique in that participants repeatedly subordinated certain interests of their respective companies in contributing to attainment of the end objectives of the program.

Meaning of Certifications

In the embryonic stages of the program, MCAIR representatives were present in a meeting wherein wire suppliers' representatives were questioned concerning the real significance of "suppliers' certifications". This question was prefaced by MCAIR Quality Assurance stating that a recently received and inspected shipment of Mil W 22759/11 wire exhibited numerous insulation faults and consequent dielectric failures although accompanied by documentation certifying that the wire met all requirements of the military specifications. In response it was explained, by an authoritative supplier representative, that the certification merely meant that the specific lot had satisfactorily passed applicable tests and inspections at the "supplier's" facilities and should not be interpreted as implying that the same lot would prove acceptable if subsequently tested in a similar manner by MCAIR. Explanation of the reason for this interpretation of the meaning of a certification being that "Wet Dielectric Testing" produced a "Corona Effect" which in turn caused degradation of the insulation, and that each subsequent wet test would produce additional defectives.

Wet Dielectric Testing Mandatory

At this point in the program the "Wet Dielectric" testing method was the only authorized method approved by Mil Specification W 22759-B as a mandatory requirement for acceptance and applicable to all wire processors. Considering the combination of a mandatory requirement for wet testing and a somewhat universal agreement that such test methods caused insulation deterioration MCAIR was seemingly relegated to the untenable position of actually causing the defects concerning which rejections and complaints were subsequently originated. Despite advancement of the "Corona degradation theory" by certain wire manufacturing authorities, in the field, it should be noted that proof and/or documentation was never presented to MCAIR which was considered adequate to support such theory relative to wire insulation which was compounded and applied in compliance with applicable manufac-

turing specifications.

Things Were Actually As Bad As They Seemed

The thinking and suggestions that MCAIR would in reality be utilizing better quality wire in end products if no incoming dielectric tests were performed was considered by MCAIR to be a logical deduction on the basis of the premises made but surely not an acceptable solution to MCAIR's known problems. MCAIR instead conducted a short term 100% testing exercise utilizing the "wet" test to establish the actual severity of the problem. It was found that the rejection rate was a startling 55%. In reaction to determining this abnormally high rate of failure, it was decided to continue testing of all incoming shipments. However, in view of the high volume of usage by MCAIR and the cumbersome procedure required to wet test in accordance with specifications, it was judged necessary to create a sampling plan. The sampling plan was also considered to be the only logical route in view of the test time factor equated to the production line usage rate. The sampling plan introduced was then closely monitored regarding all incoming shipments. Lots which were not acceptable on the basis of the samples tested were returned to the applicable supplier. Concurrent with this testing procedure records were compiled to permit evaluation of the relative quality of wire received from various sources. On the basis of these records and in the interest of immediately upgrading the quality of wire being used in MCAIR products, pending the proposed general improvements we intended to effect, MCAIR procurement department was advised of the most probable sources of acceptable wire. Subsequent orders were placed accordingly, and intensified efforts were made to encourage and work in coordination with other sources toward improvement, in view of the apparent industry-wide scope of the problem. In reviewing and evaluating the operations of some suppliers it was found that in certain instances it would have been impossible to 100% wet test a specific shipment because of the size of the lot as compared to the time interval which would have been required using equipment available. This finding verified MCAIR suspicions that at least some previous shipments had not in fact been 100% tested prior to submission to MCAIR. Despite the emphasis being placed on the importance of proper inspection and testing, by both suppliers and MCAIR, it was realized that these checks, in themselves, could not improve the basic quality of wire/cable, and that positive improvements must be made in manufacturing processes and facilities. This message was repeatedly conveyed to the various suppliers along with exhibits giving materialistic evidence of the types of discrepancies being detected by MCAIR.

Wire Processors Respond

Survey of suppliers' facilities, in company with the suppliers' representatives, brought to light the fact that in some cases the lack of adequate tool control and inspection procedures regarding extruding tips and dies was responsible for certain types of insulation deficiencies. It was also found that teflon mixing and preform rooms were insufficiently clean and lacking in necessary environmental controls. These conditions, in turn, contributed to insulation problems in the form of excessive contaminants, surface imperfections, cuts, scratches, abrasions, subsurface voids, pits, etc.

In meeting individually and collectively with wire processors' representatives and personnel of various other associated companies, plans were evolved to pursue a number of aspects of the overall problem. Many meetings, seminars, etc. ensued with improvements being accomplished as a result of efforts of each participating company.

Oops With improvements being accomplished on an industry-wide basis and the sampling plan at MCAIR seemingly controlling the quality of wire actually progressing to MCAIR assembly stages the horizon seemed to be brightening. Fate, however, would not permit such a premature solution to such a gross problem. Red Plague Struck! Some four and one-half million feet of teflon (hook-up) wire was discovered to contain varying degrees of Red Plague. Naturally, diverting of this huge quantity of wire from the production cycle created intolerable shortages thus interrupting normal progression of the wire improvement program. In deference to the planned program it now became necessary to divert some wire from normal planned verification, and data accumulation sequences. In order to assure continuation of MCAIR production scheduled, it was necessary to temporarily institute a source acceptance program. MCAIR Outside Production Quality Assurance personnel were utilized to maintain surveillance and accept wire at the various wire suppliers' facilities. This change temporarily interrupted the planned collection of MCAIR inhouse failure data. The total impact of the "Red Plague" exercise gave impressive testimony to the need for drastic change in the methods of verifying the integrity of insulation, particularly regarding successive wet testings.

Although revision "C" to Mil W 22759 was released at this point and now permitted impulse type testing using the annular ring electrode the referee in case of controversy was still the "Wet Test".

Equipment Needs And Testing Methods Studied

It was realized that with reinstitution of volume testing at MCAIR there would, unless

remedied, be a long term problem connected with the testing of wire which in turn would hamper the overall attempt to prompt advancement of the state of the art concerning the quality of wire being submitted to aerospace manufacturers. This situation was occasioned by MCAIR's lack of either impulse testing equipment and/or lack of automatic equipment for "Wet Dielectric" testing. MCAIR personnel involved in this program determined that most certainly MCAIR needed a more efficient means of verifying the integrity of large volumes of incoming wire and the only real uncertainty being precisely what type of equipment would be preferable and in concert with what might eventually be the universally accepted and authorized test method. In question was the annulated ring, bead chain, brush electrode, high frequency sine wave in conjunction with the bead chain, DC testing, etc. Despite the uncertainty as to which type electrode and power source would ultimately prove to be the most desireable, there was a basic need for sophisticated respooling equipment. Since such respooling equipment could accommodate any of the various power sources or electrodes it was determined that an all out effort must be made to obtain this basic machinery.

At this time industry at large seemed to be groping for the most appropriate method of testing insulation dielectric properties. Such test method must be capable of assuring the detection of potentially harmful insulation deficiencies while not degrading the test item by duplicate tests, or imposing excessively stringent acceptance standards on either the wire processors or end users.

Insulation Testing Seminar

In view of the variety of opinions expressed by authorities in the equipment and testing fields concerning both the advantages and disadvantages of certain types of equipment it was decided that a seminar of national scope should be arranged which foreseeably might serve two prime purposes; first, result in industry-wide unanimity regarding the type of test equipment and test criteria for universal use, and secondly MCAIR would elicit information necessary to properly equip testing and inspection facilities for long term currency to Mil Spec. test criteria.

The "Seminar on Dielectric Testing of Aircraft Electrical Hook Up Wire" was arranged and conducted at MCAIR on 28 April 1970. Speakers were: Ronald Soloman - McDonnell Aircraft Company, Richard Wilkes - Hipotronics Inc., Harold Endicott - Engineering Consultant, Lou Frisco - Director of Manufacturing Raychem Corporation, Jerry Leary - ITT Surprenant, Joseph Reed - Technical Specialist E. I. DuPont, Plastics Dept., Thomas Stewart - Process Engineer Haveg Industries, Richard Thayer - Director of Technical Services Tensolite Insulated Wire. The speakers were asked to address themselves to the following subjects:

A. What type of dielectric test equipment will insure the best dielectric integrity of an insulation?

B. Does some equipment do a better job on an extruded insulation than on a tape wrapped insulation?

C. What are peculiarities of testing tape wrapped insulations?

D. How compatible is dry dielectric equipment with wet tank?

E. What supporting test data can you offer to establish the superiority of a given type of equipment?

F. What are advantages and disadvantages of wet tank test?

G. What about cost of purchase, setup, operation and maintenance of different types of dry dielectric test equipment? What human factors are critical to successful operation?

H. Some consideration is being given to using a power source with a brush tandem. Evaluate this consideration.

I. Make a firm recommendation for a dielectric test system to insure good dielectric integrity of wire to be used at McDonnell.

In addition to the scheduled speakers, there was a very gratifying attendance of concerned personnel representing various types of companies, plus representatives from a number of MCAIR internal departments. Responses to speakers' presentations and ensuing discussions were rather scintillating and most informative. In fact, subsequent to the seminar comments were received extolling the merits of this type of opportunity to collectively review and discuss the latest thinking and techniques relative to important and mutually interesting subjects such as the "Electrical Wire Dielectric Testing" Seminar.

Although the "pay off" probably varied somewhat depending upon the basic interest of each attendee, it did provide a more definitive course of direction for the "Wire Improvement Program", being spearheaded by MCAIR. There appeared to be two immediate objectives the attainment of which would alleviate a long term trouble area.

Establishment of an alternate dielectric test which would be equal to or better than the wet tank, and equally suitable to the wire manufacturer, the wire user, and the customer for the end product.

The collection of dielectric test and failure data necessary to convince the military of the equivalence and acceptableness of the proposed new test method. Solicitation of wire manufacturers' support concurrent with test data acquisition efforts. Pursue incorporation of the proposed test into all military wire specifications.

Annular Electrode Questioned

Most military wire specifications in existence at the time permitted impulse dielectric testing utilizing the annular electrode. However, with the use of the annular electrode, the test data analysis raised questions concerning the equivalence of this combination as compared to the wet tank test. MCAIR, therefore, continued to require that wire manufactured for MCAIR use be 100% "wet tested". All applicable purchase orders were so annotated and accepted as a contract condition by the Wire Suppliers. Impulse electrodes to be considered and evaluated were the "Brush Electrode" and the "Miniature Bead Chain Electrode". Both could, incidentally, be powered by the same impulse power source. (Several types being currently on the market.) Working in coordination with Wire Suppliers MCAIR commenced a testing study comparing the results of "impulse testing" with the results obtained by the "wet test" method. Impulse testing was accomplished using the "BR-1 Brush" type electrode and 11.KV test voltage. The wet test, of course, required testing at 2.2KV. Approximately 3½ million feet of wire was used in conducting these tests with the impulse test being performed first and followed by the wet test.

Impulse Versus Wet Test Equivalency Established

The results were a very near equivalency of capabilities of detecting dielectric failures. This exercise provided more confidence that an equal or better substitute for "Wet" testing was feasible and that further research and effort was justified. An added incentive for securing a universally acceptable substitute for the Wet test was the fact that although wire/cable of Tape Wrap Construction was being considered for use on the F-15 aircraft and MCAIR Engineering was evidencing opposition to exposing any type wire or cable, to be used on this project to the tank test. Also MCAIR Quality Assurance elected to 100% dielectric test all wire to be used on DC-10 Wing components.

Considering the ever mounting requirements for verification testing of incoming wire, the limitations of MCAIR wet testing equipment, and the increasing problem of maintaining adequate supplies to support the production line, it became ever more evident that as a minimum MCAIR would need a more sophisticated means of assuring the quality of wire intended for McDonnell Douglas (MDC) products. It continued, however, to appear possible to resolve MCAIR's internal problems while at the same time hammering out an improved and acceptable wire testing system which would be applicable, and beneficial, to other wire users and wire processors on a national basis.

MCAIR Equipment Needs

With these dual objectives in mind and bolstered by a realization of the significance of the achievements, if these goals were attained, added impetus was given the program. Immediately steps were taken to determine the type of spooling/respooling equipment preferred, the most adaptable power source, and the most promising type electrode. Information resulting from the Seminar of 28 April 1970 was very instrumental in directing MCAIR in the search for the needed testing equipment. As the MCAIR team arrived at conclusions concerning the specific equipment preferred it became necessary to secure internal authorizations for actual procurement. This particular step in the program did not prove to be a simple operation, as it became necessary to, figuratively, sell the proposed testing procedure, and preferred testing equipment to a number of internal disciplines, such as:

- Quality Assurance Management
- Electrical Engineering
- Electrical Planning
- Equipment Engineering
- Manufacturing Authorities
- Corporate Management
- Budget Representatives
- Procurement (Single Source vs Competitive Bids)
- Standards Engineering
- Materials and Processes Engineering
- Staff Engineering

Formal Proposal For Equipment

It became quite apparent that it would be necessary to sequentially explain, and justify to each of these departments involved the basic reasons why the changes and associated expenditures were being sought. Since the basics of a very comprehensive problem would have to be explained a number of times it was decided that a formal written proposal would be prepared and provided to all concerned departments. This documented "Proposal

For Inspection, Testing and Handling of Incoming Bulk Electric Wire" did prove to be very instrumental in conveying the message. There were, however, decisions to be made such as, make or buy, and whether single source or competitive bid type procurement was the most logical approach.

New Equipment Acquired

Subsequently, 20 November 1970, MCAIR took delivery of a commercially available Impulse/Respooler machine capable of adaption to the variety of electrodes being considered. This acquisition now permitted MCAIR to conduct in-house evaluations of impulse testing utilizing several types of electrodes as compared to the wet test method.

Incidently, prior to placing this equipment in use calibration checks were performed, adjustments made, etc., to assure that subsequent test data were reliable. In this respect the "power source" manufacturer provided technical assistance relative to his component.

Miniature Chain Bead Electrode

As a result of consultations and numerous tests to equate the various types of electrodes it was determined that the "miniature bead chain" was the most promising type electrode to serve the intent of the overall program.

Next in the sequence of steps was a need to establish optimum test voltages, pulses to wire speeds, etc., in order to achieve a severity of test comparable to the wet test, which was generally conceded to be an established and sufficiently severe test capable of revealing potentially harmful wire imperfections.

Test lots (approximately 2½ million feet total) were alternately tested by Wet Test method followed by impulse, then impulse followed by Wet Test. Planned into this series of tests were controlled and tabulated variations in applied impulse test voltages and wire speeds. Many types of wire/cable configurations which were manufactured to Military Specifications 81381, 81044, 22759 and 16878 were the prime test specimens.

A "Guinea Pig" test spool was created which consisted of approximately 800 feet of wire containing several original manufacturing defects, and to which a number of both common and uncommon defects were added. This spool subsequently served in a "proof" type capacity through some 100 tests by both MCAIR and other participants in the program. Periodic verification of equipment calibration was one of the uses of this spool. This spool was also tested at numerous voltages ranging from 7.5KV through 11.5KV, at wire speeds of 100FPM - through 300FPM. Repeatability of the impulse equipment and testing method proved to be excellent.

Optimum Impulse Test Voltage Established

Findings and determinations resulting from these tests were that in the consensus of opinions the optimum impulse test parameters was a voltage of 10KV at a wire speed of 300FPM. These established impulse test criteria would result in a test which is somewhat more stringent than the "Wet Test" method but which was agreed to be necessary and preferred in order to assure the required degree of perfection of insulation, minimize the necessity of repeated verification tests, and assure credence of the test, and therefore, confidence in the accepted product.

Supplier/User Agreement In a subsequent meeting of major wire processor's representatives, participating in the wire improvement program, and MCAIR personnel an agreement was reached in that impulse testing at 10KV test voltage using the miniature chain bead and a wire speed of 300FPM would be considered as an authoritative basis for acceptance or rejection by both the Wire Processors and MCAIR. This joint decision also eliminated the need for any referee tests, and was intended to prevent contesting of test results. It was also agreed that evaluation tests would continue at both MCAIR and Wire Processor's facilities to compile more data, with the ultimate objective being to obtain a revision of Military Wire Specifications, wherein the described test procedure would be incorporated with the exclusion of both the "Wet Test" and Annular Ring Electrode Methods.

Ground Work Laid For Military Specification Revisions

Concurrent with continuation of the testing/evaluation program MCAIR representatives consulted with Government Military Officials responsible for content and control of Military Specifications. The purpose of these contacts was to brief these authorities regarding the intentions of Wire Processors, Wire Users, and other concerned participants in the program, to lay necessary ground work, and to "feel the pulse" of the military relative to the impending proposals.

The reaction of these authorities was most gratifying and had the effect of further motivating proponents of the changes. Although expressing agreement with the approach and basic concepts being promoted there was a request that the military be kept informed of the progress of the study and ensuing phases of the data accumulation efforts.

NEMA Consulted

Upon accumulation, and tabulation, of an

EXHIBIT "A"

MCAIR IMPULSE/TANK RESULTS

DEFECTIVES ⟶ 7/24 ⟵ LENGTHS TESTED

** KV - At which lengths failed wet test

- No tank failures in lengths previously impulse tested at 11 KV

TEFLON

Part Number	Gauge	Reel	Footage	Length	Order of Tests	"A" Failures Impulse Voltage 8.5	9.5	10	10.5	11	"B" Failures Tank Voltage 1750	2200	2500	Comments
22759/11	16	9	25,255	99	AB	0/99	-	-	-	-	-	8/99	-	** .6,.9,.9,1.1,2.2,2.2,2.2,2.2
22759/11	16	1	3,969	15	AB	0/15	-	-	-	-	-	2/15	-	** 1.2,2.2
22759/11	20	1	714	1	BA	0/1	-	-	-	-	-	0/1	-	
22759/11	18	1	422	1	BA	0/1	-	-	-	-	-	0/1	-	
22759/11	18	1	1,403	11	AB	0/11	-	-	-	-	-	1/11	-	** 1.1
22759/11	20	1	1,192	3	AB	1/3	-	-	-	-	-	1/3	-	Impulse verified in tank
22759/11	16	5	3,176	49S	AB	3/25	-	-	-	7/24	1/39	-	-	# 8.5 impulse failed tank
22759/11	16	12	51,830	171S	AB	1/85	-	-	-	2/86	2/168	-	-	# 8.5 impulse failed tank
5M1005UO	20-4	4	3,165	4S	*ABA	*0/2	-	-	-	2/2	1/2	-	-	#*8.5 impulse failed tank
22759/7	22	1	1,996	8	*ABA	-	*0/8	-	1/8	-	-	-	0/8	
22759/7	20	1	550	2	BA	-	0/2	-	-	-	-	-	0/2	
22759/7	16	1	220	1	BA	-	0/1	-	-	-	-	-	0/1	
22759/7	18	1	330	1	BA	-	-	0/1	-	-	-	-	0/1	
21985	20	5	21,645	68	AB	-	-	-	8/68	-	-	0/15	-	15 tank only (Reduced Qty. W/Tested)
22759/11	18	1	3,300	13	AB	-	-	6/13	-	-	-	0/7	-	
22759/11	18	1	3,300	10	AB	-	-	2/10	-	-	-	0/8	-	
22759/11	18	1	3,278	9	AB	-	-	7/9	-	-	-	-	0/2	
22759/11	18	1	3,193	13	AB	-	-	4/13	-	-	-	-	0/9	
5M1005UO	16-3	16	19,970	80	AB	-	-	59/80	-	-	-	0/21	-	21 tank only (Reduced Qty. W/Tested)
22759/11	16	14	56,854	189S	AB	3/94	-	-	-	7/95	-	*21/140	-	# 94@8.5, 95@11, 140 tank, *8.5 impulse failed tank

additional one million feet of wire test data (Exhibit "A" being an example page reflecting the method used to tabulate test data) MCAIR representatives attended a meeting of the National Electrical Manufacturer's Association (NEMA) to obtain comments and endorsement by the NEMA relative to the course being pursued and the ultimate objectives of the program. After considerable discussion the NEMA committee agreed that the data presented by MCAIR offered impressive evidence to support eventual adoption of the "Miniature Bead Chain" type of impulse electrode and test methods being proposed. The committee adopted a resolution recommending use of the bead chain/impulse test method and suggested that the MCAIR program continue efforts to have this method of testing incorporated into applicable military specifications.

Fortified by the NEMA committee resolution and backing, and armed with impressive test documentation MCAIR representatives attended a meeting in Washington DC with the Government officials responsible for Military Specifications for the express purpose of further updating these gentlemen, as was their previous request. The data offered and the case presented, was again very well received and MCAIR representatives were, in essence, advised to go forth and seek the additional concurrence of the SOCIETY OF AUTOMOTIVE ENGINEERS (SAE - A2H). A verbal commitment was obtained at this time to the effect that upon securing agreement and approval by NEMA, and SAE - A2H, regarding the proposals, Naval Air Systems Command would duly revise Military Specifications.

Inspired by successes, awed by further challenges, and enthused at prospects, MCAIR proceeded by recognizing that to accomplish the next series of objectives it would be advantageous to further reinforce our case with additional test data.

SAE - A2H Committee

By the time the SAE - A2H meeting had convened, 18 May 1971 (Atlanta, Ga.) MCAIR had compiled test data far in excess of $6\frac{1}{2}$ million feet of wire, and had obtained the support of a number of other concerned sources. The accumulated test data as summarized reveals that:

- o A specific lot of wire when tested by the miniature bead chain impulse method at "8.5KV" resulted in a failure rate of 2%. Subsequent test of the same lot (with impulse detected failures removed) by the "wet" dielectric method resulted in a failure rate of 11%.

- o Another lot when impulse tested in the same manner, except at a raised test voltage of 10.KV, resulted in a failure rate of 21%. When subsequently wet dielectric tested there were no additional failures.

The following committee recommendations resulted from this meeting:

A. "The miniature bead chain electrode should be used as a replacement for the annular electrode in the dielectric test and the revised impulse test should be used as a replacement for the tank test. The description of the annular ring electrode and the dielectric tank test should be deleted from all Military Specifications."

B. "A test potential of 10.0KV should be used in conjunction with the miniature bead chain electrode for all wires that presently require a 2200 or 2500 volt dielectric tank potential."

In addition, it was recommended that test method "3016" be rewritten so that definitions of the impulse power source, the test electrode, and general operating parameters were compatible with this new test method being advocated. This test method (3016) was also proposed to be updated concerning other types of information.

Military Specifications Revisions

On 27 May 1971 MCAIR received, official, correspondence from the Naval Air Systems Command wherein directives were being given to incorporate the following dielectric test procedures into Military Specifications 8138, 16878, 22759 and 81044. The annular impulse and wet tank test will be deleted from the foregoing specifications, and replaced by an impulse bead chain test utilizing a voltage of 10KV. This replacement test method to be used where tank test at 2.2KV or 2.5KV voltage was formerly specified. In addition, test method 3016, revised as follows will be incorporated in these specifications.

Method 3016, Dated 26 May 1971
Impulse Dielectric

Scope

This test is to be used for dielectric proof testing of insulation on unshielded and unjacketed wires and cables.

Samples

One hundred percent of the wire and cable shall be subjected to this test.

Test Equipment

The electrode head through which the

wire is passed in the impulse dielectric test shall be as shown in Figure 1 for AWG 26-8 and Figure 2 for AWG 6 and larger. The equipment shall meet the following requirements.

Impulse Waveform - The waveform of the voltage applied to the electrode shall consist of a negative pulse followed by a damped oscillation. The negative pulse shall have a maximum 0-90% rise-time of 75 microseconds. The pulse repetition rate shall be between 200 and 250 pulses per second, inclusive. The specified voltage shall be defined as the peak magnitude of the initial negative pulse. The peak magnitude of the first positive overshoot and each of the following damped oscillations shall be smaller in magnitude than the initial negative pulse. The waveform shall be analyzed to determine how much time each pulse and corresponding damped oscillation (both positive and negative) remains at an absolute potential of 80% or greater of the set peak voltage. This time duration shall be 20 to 100 microseconds.

Voltmeter - A voltmeter indicating the peak value of the initial negative pulse, connected to the electrode head, shall continually indicate the electrode potential. The full scale meter reading shall be no greater than 25 KVp. The meter accuracy shall be such that when the voltage is adjusted to the specified value per the instrument voltmeter, the actual electrode value shall be within ±5% of the indicated voltage. The meter shall maintain specified accuracy for a minimum period of at least one month after calibration.

Capacitive Regulation - The output voltage shall decrease no more than 12% when an initial capacitive load of 25 picofarads between electrode and instrument ground is increased to 50 picofarads.

Failure Detection Circuit - There shall be a failure detection circuit which will give a visible or audible indication of a dielectric failure, so that the wire can be stopped and the defective portion can be removed. The fault detection circuit shall be sufficiently sensitive so that a fault is indicated at the test voltage when the electrode is arced to ground through a 20 kilohm resistor. The unit shall also be capable of detecting a fault which lasts for the duration of only one impulse.

Test Procedure

The insulated wire shall be threaded through the electrode head and all conductors grounded at both ends. With the electrode head energized to the specified voltage, the wire shall pass from the pay-off spool, through the electrode and on to the take-up spool. The voltage shall be adjusted with the wire or cable in the electrode.

The wire or cable running speed shall be between 25 and 650 feet per minute, inclusive. If any dielectric failures occur they must be cut out and removed along with at least 6 inches of wire on each side of the fault. The equipment shall be so wired as to automatically de-energize the high voltage when the wire is stopped. During the string-up of a new length, every attempt shall be made to expose the entire length including ends to the requested voltage. Any ends not tested shall be clearly marked and removed subsequent to this test.

Calibration of Voltmeter

An external voltmeter, capable of indicating the peak value with or without auxiliary circuitry, shall be connected to one of the electrode beads directly or via a calibrated attenuator circuit. The instrument voltmeter shall be checked for accuracy at each specified voltage that the equipment is intended to operate at. An alternate calibration procedure is the use of a calibrated oscilloscope, connected to the bead electrode via a suitable attenuator. The peak magnitude of the initial negative pulse may then be read directly from the waveform display. An oscilloscope will be necessary in any case in order to verify conformance to the waveform parameters as specified in second paragraph under "Test Equipment".

Results

One hundred percent of the wire or cable on the take-up spool shall have been submitted to the Impulse Dielectric test. All failures shall have been removed.

Conclusions

With attainment of revisions to these Military Specifications MCAIR has assessed total results of the program and reached the following conclusions:

1. With establishment of a single specific type of dielectric test, made mandatory by Military Specifications, there should be a universal understanding as to the degree of insulation perfection required relative to the types of wire/cable discussed. Wire Processors may, consequently, refine manufacturing operations to the degree necessary to correspond.

2. Wire users may conduct verification inspections/tests to the extent considered necessary, and with satisfaction that in the event a fault is detected there will be no, or a very minimal amount of, controversy concerning the testing, techniques, etc.

3. Elimination of the "Wet Test" as a Military Specification requirement should produce quite a number of benefits. Degradation of insulation due to testing should be greatly reduced, if not eliminated. (Repeated tests with the "Guinea Pig" spool attests to this deduction.) The phenomenon of "Water Wicking" and the results should be minimized or nil. The time consuming and cumbersome handling methods required to "Wet Test" are replaced by much more efficient and economical handling methods.

4. Although MCAIR and Wire Processors suffered certain labor pains during the gestation period of the program, the offspring is a general upgrading of products which will be beneficial to aerospace users on an industry-wide basis.

5. MCAIR's wire/cable testing and verification capabilities have been greatly enhanced, and it should be necessary to return only a very limited amount of wire to suppliers.

6. Customers for Aerospace products should reap a number of real and intangible benefits.

7. We believe that in evaluation of the results obtained through this program lies the answers to questions posed during the conceptual stages of the program.

It should be understood that MCAIR had no intentions, and does not at this time have intention, of becoming an Inspection/testing agency, as such, for these products. It is rather MCAIR's plans to increase and/or decrease inspection and testing efforts in these respects as the quality of products received from various sources dictates necessary.

For the benefit of user companies which may prefer to institute a program comparable to that currently in use at MCAIR it should be mentioned that the cost of equipping this type of operation is not prohibitive and may in some instances be off-set by converting from another system.

Acknowledgements

The authors acknowledge appreciation for the assistance and understanding of the many persons who cooperated with this endeavor. In particular, our thanks go to Personnel of MCAIR Internal Departments, Wire and Cable Processors, Conductor Manufacturers, Product Developers, Equipment Companies, and Government Authorities. The experiences were both rewarding and a pleasure.

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PARAMETERS AFFECTING THE ABILITY OF INSULATION ON SOLID CONDUCTOR WIRE TO WITHSTAND CUT-THROUGH

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Summary

The work presented herein on cut-through testing presents the results obtained on nine different wire insulations with a controlled test. The controlled test includes test apparatus which is a balanced beam. On one side is a cutting tool which cuts into wire placed beneath it on an height adjustable anvil. NBS Class III ring weights are placed on the beam over the cutting tool to supply the vertical cutting force. The beam is cam controlled so that the cutter may be placed upon the wire at a prescribed reproducible speed. The wire supports the cutting tool for one hour. The insulation between the cutting tool and conductor is then tested for dielectric withstand voltage. Passing the withstand test is defined as passing cut-through.

Background

When the Strategic Systems Project Office of the Department of the Navy first instituted solderless wrap terminations in computer systems[1], the wire specified for use was nylon jacketed PVC insulated AWG 24 tin-coated solid copper wire. Of prime concern was the ability of the wire insulation to withstand the rigors of the environment of sharp edged wraposts. The wrapost edge was designed so as to indent and be indented by the wire in effecting the solderless wrapped termination. The insulation, however, was not supposed to be indented by wraposts to which it was not connected. It had to be tough enough to withstand cutting by the sharp edge.

When smaller grids on backpanels became feasible, smaller wraposts and smaller gage wire were also used. Also, space became important with the advent of the 0.1 inch grid and the wire insulation wall thickness had to be reduced.

Originally the AWG 24 wire had a total insulation wall thickness of 15 mils. Now we specify 7 mils for AWG 24 wall thickness. Use of AWG 24 wire has diminished and AWG 30 is used. The wall thickness for AWG 30 wire is 4.75 mils.

Previously we had been blessed by a heavy wall of one of the toughest insulation types available. By 1967 the situation had changed. Nylon jacketed PVC wire with 4.75 mil wall with AWG 30 solid conductor is difficult to make. The difficulty arose in the tolerance necessary on the finished diameter which allowed the wire to be used by automated solderless wrap termination machines. Wire Specification WS-6118/1 specifies AWG 30 wire as 0.0195 ± 0.0015 inches in overall diameter.

This tolerance of ± 1.5 mils brought new headaches. New insulation systems were developed to meet this tolerance but no previous experience with them, even with stranded conductors, was available. They had been developed for this system, and this system had to evaluate them.

Not only did we have to find out heat resistance, cold bend, dielectric breakdown strength, ad infinitum, ad nauseum; now we had to find out what its cut-through ability was.

Problem? You bet. How do you test for cut-through? What is cut-through? Wire insulation in its point-to-point routing on a back panel comes into contact with wraposts whose edges may cut into the wire insulation if the wire is pressed against the edge of the wrapost. If, within one hour after manufacture, such a wire shows unwanted continuity to a wrapost to which it is not deliberately terminated, the insulation has exhibited "cut-through". "Cut-through" for the purposes of testing must be further defined.

In testing, a "standard" cutting tool was designed with a 90° included angle to simulate the 90° corner of the wrapost. This was to be pressed under static load into the wire insulation. After one hour a dielectric withstand test voltage would be applied between conductor and cutting edge. If the dielectric test indicated failure, the specimen had failed "cut-through". Actually "cut-through" occurs at the load which in one hour causes the insulation to fail in the dielectric withstand test.

Original Cut-Through Testing

Originally in the first testing a number of variables were considered important.[2,3] They were:

a. Insulation type

b. Wall thickness

c. Diameter of solid conductor

d. Sharpness of cutter

e. Load (this was controlled)

f. Time (this was held constant at 1 hr.)

g. Dielectric withstand voltage level

h. Speed of applying cutter to insulation

In that testing we found:

a. there was a difference between insulation types

b. that we didn't have enough data to determine what effect the wall thickness had on cut-through results

c. that we did't have enough data to show what effect the diameter of the conductor had on cut-through results

d. that with sharp cutters cut-through occurred at lower loads than with .003 inch radius cutter

e. that lower test voltages usually require increased loads to obtain cut-through

f. that reduced speed in applying the cutter to the insulation results in increased loads to obtain cut-through.

The original goals still had not been satisfied. We did not know:

a. what cutter was best

b. which dielectric test was best

c. what loads to specify for each insulation type and AWG size.

The methods of obtaining data up to this time limited the types of analysis which could be performed in that statistical tools such as the "t" test and ANOVA could not be applied to all the data. It had taken three years to find out that, for the most part, all that had been accomplished was to identify which parameters to control. This in itself was no small accomplishment.

Recent Cut-Through Testing

The variables placed under control for the testing reported herein are as follows:

a. Cutting tool held at 0.003 ± .0005 inch radius

b. Time of test, 1 hr.

c. Dielectric withstand test, 500 V ac (some also run at 2000 V ac)

d. Speed of applying cutter to insulation (cam rotation 1.0 r/min max)

e. Insulation wall thickness, only wires meeting finished diameter requirements of WS-6118/1 were used (see Table I).

f. Diameter of conductor, within tolerance of applicable specification (ASTM B33 or B298 as applicable).

The testing involved determining cut-through on nine different insulation types in several AWG sizes. Several lots were tested in five of the insulation types in AWG 30 size. The cut-through load was determined in the following manner.

Ten specimens, each twelve inches long, were selected from a total sample length of twenty-five feet. These were placed in the stations of the cut-through tester. Equal weights (NBS ring type) were placed upon each station. The cutter was lowered at a 1 r/min cam rotation until the insulation supported the cutter and load. After one hour the insulation at each station was subjected to a 500 V rms test voltage. If no electrical breakdown was found, the load was removed and the wire positioned to provide a new area of test on the same specimens. The load was increased by 100 grams (g) on all stations and the test procedure repeated until electrical failure occurred on all ten stations. Each wire type and lot was so tested. In addition on some specimens, if there were no failure at 500 V ac, the voltage was increased to 2000 V ac and held for an additional minute. The results of this testing is shown in Table II, "Master Chart of Cut-Through Values (g)". On rows where nothing appears, no test was performed. On rows where " - " appears, the value was above 4000 g (4000 g being the maximum weight that could conveniently be placed on the test station). The value that is recorded is the load in grams at which failure first occurs for that station.

TABLE I.

FINISHED WIRE DIAMETER (INCHES)

Wire size AWG	Diameter
30	0.0195 ± .001
28	0.0265 ± .0015
26	0.0295 ± .0015
24	0.0345 ± .0015
22	0.039 ± .002
20	0.046 ± .002
18	0.054 ± .003

Two types of cutters are shown, i.e., GE and NAFI (5 each). Actually these cutters were made to have 0.003 ± .0005 inch radius cutting edge. The five from GE are made from tungsten carbide, while NAFI's are of tool steel.

Analysis of Results

In analyzing the data there appeared to be a difference in load between stations (compare columns in Table II). On AWG 30 wire which was tested at both 500 V ac and 2000 V ac, the significance in difference between stations was determined by paired variate "t" test. The results of these "t" tests are shown in Graph I. The average load shown is the average of the column. If there is a significant difference (10% level or less), it is noted by "yes"; non-significance by "no". Also shown in Graph I are the results of paired variate "t" tests comparing station 1 at 500 V ac with station 1 at 2000 V ac and so forth. These are the "vertical" comparisons shown in Graph I. These results, comparing load at 500 V ac with load at 2000 V ac confirm results obtained previously[2]. Only one station (#6) in the ten shows non-significance in the loads at 500 V ac and 2000 V ac. Notice also the difference shown in NAFI cutters #9 and #10 compared to the remaining eight. All the cutters were removed and examined by shadow graph and no difference was seen, yet the data say there is. Generally, if the difference is over 60 g, it is significant; if below 60 g, it is not significant. Hence, the testing could probably be refined by using 50 g increments, rather than 100 g.

There seemed to be an increase in difference in average load between GE and NAFI cutters at 500 V ac. Since Graph I showed significance between some which were tested at both 500 V ac and 2000 V ac, and since more data were available at 500 V ac, a new series of paired "t" tests were performed. The first cutter in each group, #1 and #6, were considered the norm for that group and each of the other cutters was compared to it as follows: 1 vs. 2, 1 vs. 3, 1 vs. 4, and 1 vs. 5; 6 vs. 7, 6 vs. 8, 6 vs. 9, and 6 vs. 10. The results are shown in Graph II. As in the analyses shown in Graph I, if the difference is above 60 g, the difference is significant; below 60 g, it is not. From these differences and loads listed in columns #1 and #6, corrections to the other columns were made to eliminate the cutter variance. The corrected data are shown in Table III.

Using the corrected data, the arithmetic average, $\bar{X}$, and standard deviation, σ, was found for each insulation type and also according to to cutter group (GE or NAFI). These statistics are shown in Table IV. From the values of $\bar{X}$ and σ, the difference between GE and NAFI loads ("t") was computed. When the difference $\Delta\bar{X}$ is plotted against $\bar{X}$ of GE data, a good straight line fit is obtained. This is shown in Graph III (the data of insulation 8 not being used). The correlation is very good. This clearly shows that the heavier the load necessary to cause cut-through, the more difference will be shown between GE and NAFI cutters. Notice, that this time, if the difference is above 50 g, significance is shown. This agrees well with the previous paired variate "t" tests.

The standard deviation, σ, also increases with increasing load in both GE and NAFI cutters. The average load, $\bar{X}$, was plotted against standard deviation, σ, and is shown in Graph IV. Straight line correlation is very good. However, σ cannot be less than zero, so the data were fit to $\bar{X}$ and log σ. This is shown in Graph V. Notice that the correlation coefficients are both about 0.93, so the choice of which to use is open. For the sake of argument, choose the log fit.

In Graph III, the difference in load between GE and NAFI cutters is given by:

$$\Delta\bar{X} = 0.16503\ \bar{X} - 94.229$$

In Graph V, the standard deviation is related to the average cut-through, $\bar{X}$, by:

$$\operatorname{Log} \sigma = 0.0007722\ \bar{X} + 1.13427$$

Solving the two equations simultaneously gives:

$$\operatorname{Log} \sigma = 0.004679\ \Delta\bar{X} + 1.5752$$

By assuming a value of "t" of 1.8 and substituting values of σ and $\Delta\bar{X}$ from the above equation in the equation for "t" and solving it for n (assuming $n_1 = n_2$ and $\sigma_1 = \sigma_2$) then estimates of the sample size necessary to show significance between GE load and NAFI load are obtained. The significance would be at approximately the 10% level. The values of n so computed are shown in Graph VI. From this then, on the average, it would take about 12 specimens tested on GE tools and another 12 specimens from the same lot tested on NAFI tools to statistically show a significant difference in load of 50 g. Keep in mind that this 50 g is a difference in tools, not in wire insulation.

The final results of testing AWG 30 wire insulations are shown in Graph VII. The ordinate and abscissa are both load in grams, therefore, the averages of the cut-through loads shown lie on the line $Y = 1.0\ X + 0$. The theoretical maximum and minimum average computed according to the formulae shown on Graph V are shown in the "Y" direction as are by the individual statistical ranges. One disparity should be kept in mind. The first three data points shown were obtained on only one sample of wire each. The remaining represent pooled data on two or more different samples of wire within each group. Hence, the statistical ranges shown on the first three are not weighted as are the others. This being so, the limits taken from Graph V may not be truly representative of the "real" world. It does, however, represent the data presented herein.

One of the purposes of this testing was to determine values of cut-through to be used as specification values. In Table II, there are only six of the insulation types tested in AWG sizes other than AWG 30. And in these, only one other size was available for testing. This is a rather meager sampling. But, for the fun of it, some curve fitting was done. All of the data of Table II in these sizes and types were used to compute the average, standard deviation, and statistical limits. These statistics are shown in Table V. The difference in cut-through load for each insulation type is shown plotted against psi/g factor[2] in Graph VIII. The formulae shown are perfect fits for the four data points (⊙). The extrapolated points (⊡) can vary appreciably, and even though "perfect" fits were obtained, they really don't mean much. It is quite obvious that the attempt to curve fit does not allow reasonable values of cut-through to be calculated for AWG 18, 20, and 22 size wire.

Conclusions

The following is a list of conclusions both previously made[2,3] and supported by the data herein:

a. Each insulation type has its own peculiar cut-through.

b. Differing lots of wire insulation within one type can differ significantly from other lots in cut-through.

c. If the test voltage is increased, the load for cut-through is decreased.

d. Increasing the rate of speed that the cutter comes into contact with the insulation will lower the load for cut-through.

e. The sharper the cutting tool the lower the load for cut-through.

f. Standard cut-through tools are difficult to make.

g. The cutters are expensive (about $16.00 each).

h. Cut-through testing is expensive (about $80.00/sample).

i. Cut-through test apparatus is expensive (about $3,000.00).

j. Testing is incomplete in that all insulation types in all AWG sizes have not been tested.

k. In AWG 30 sizes tested, reasonable failure criteria cannot be statistically determined.

Most of the above conclusions are negative, however, by controlling the variables positive conclusions can be made.

a. Reasonable mean values (arithmetic) can be established.

b. Practical (non-statistical) failure criteria can be established.

The latter two conclusions are useful only when correlation between testing laboratories has been accomplished.

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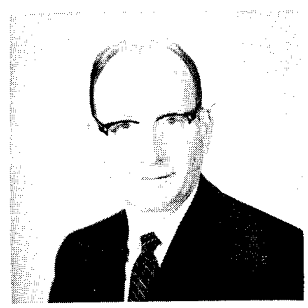
1 "Automated Wire Wrapping in Military Systems", Willard D. Watkins, Proceedings of IEEE NEREM Conference, Nov 1971.

2 "The Evaluation of the Ability of Insulation on Solid Conductor Wire-Wrap Wire to Withstand Cut-Through", Willard D. Watkins, NAFI TR-1572, (AD 872091 L).

3 "Correlation Testing Performed at General Electric Co. (GEOS) and at NAFI on the Cut-Through Test of WS-6118", Willard D. Watkins, NAFI TR-1575 (AD 871965 L).



E. F. Timpane

Mr. Timpane graduated from Siena College in 1949 with a B.S. degree in Chemistry. In 1951, after obtaining his M.S. degree in Physical Chemistry, he joined the General Electric Company Transformer division in Pittsfield, Massachusetts. From 1951 to 1969 Mr. Timpane was engaged in studies relating to the physical-chemical properties of transformer insulation systems. Since 1969 he has been manager of Quality Control, In-Process Control at General Electric's Ordnance Systems in Pittsfield.

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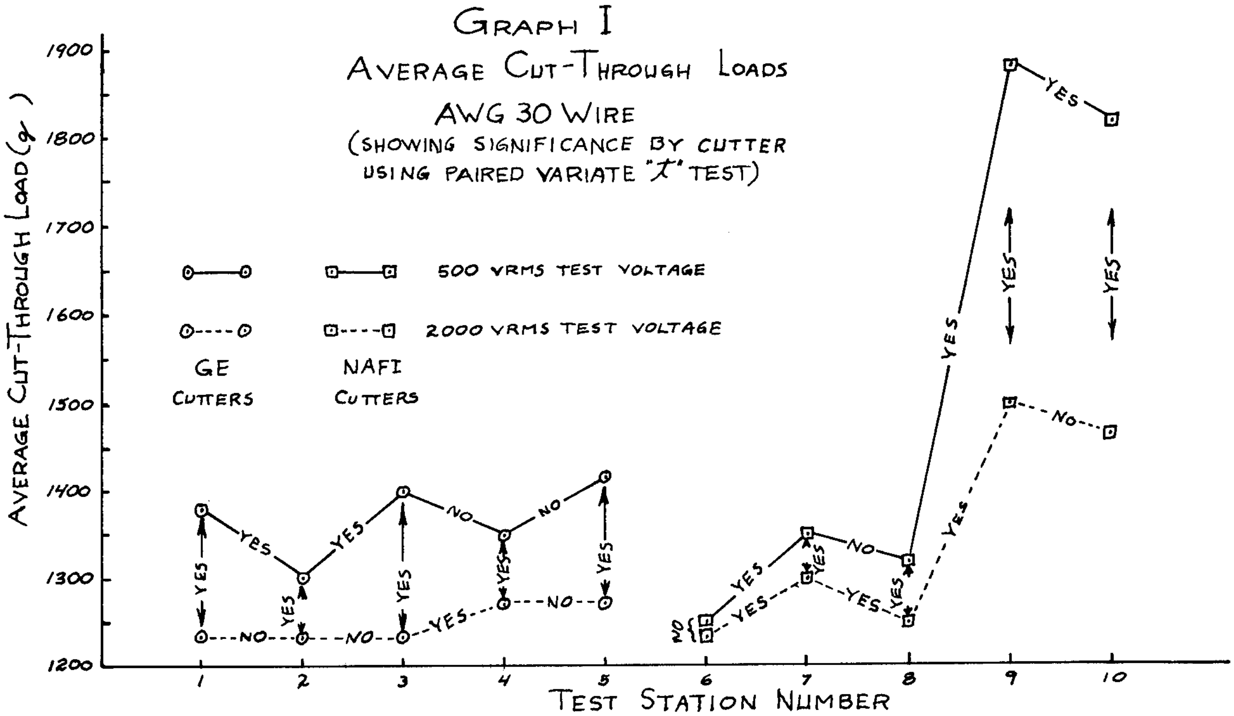
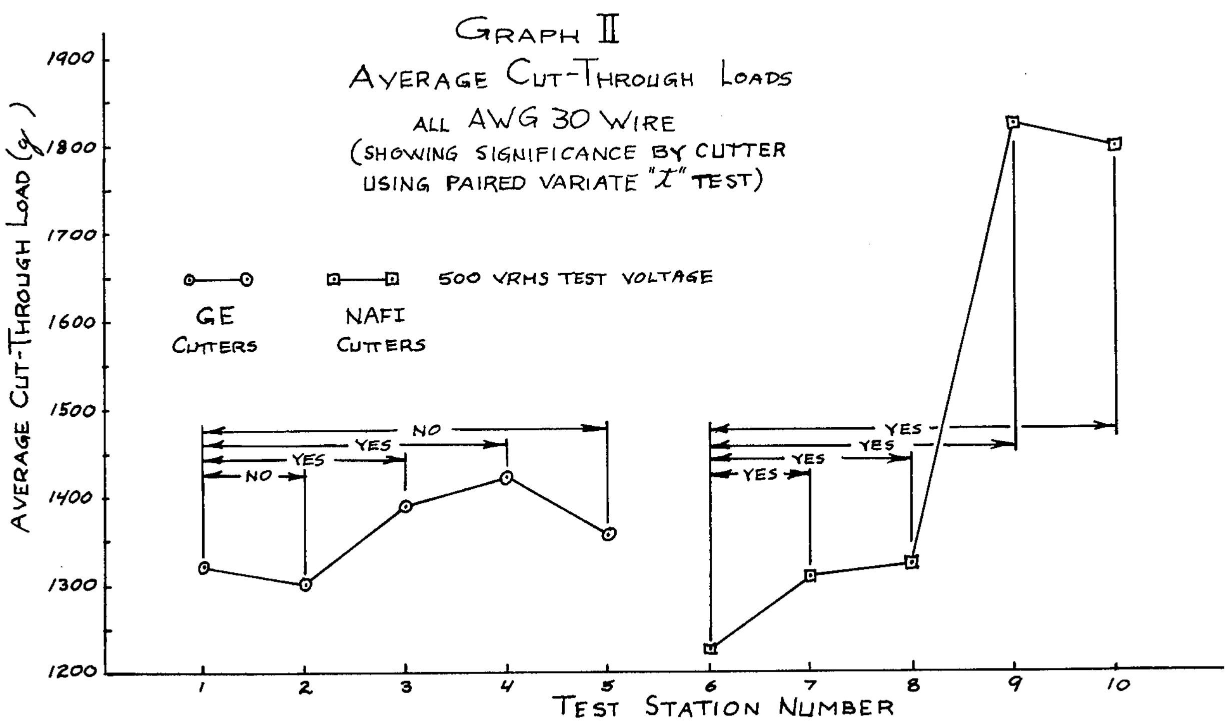
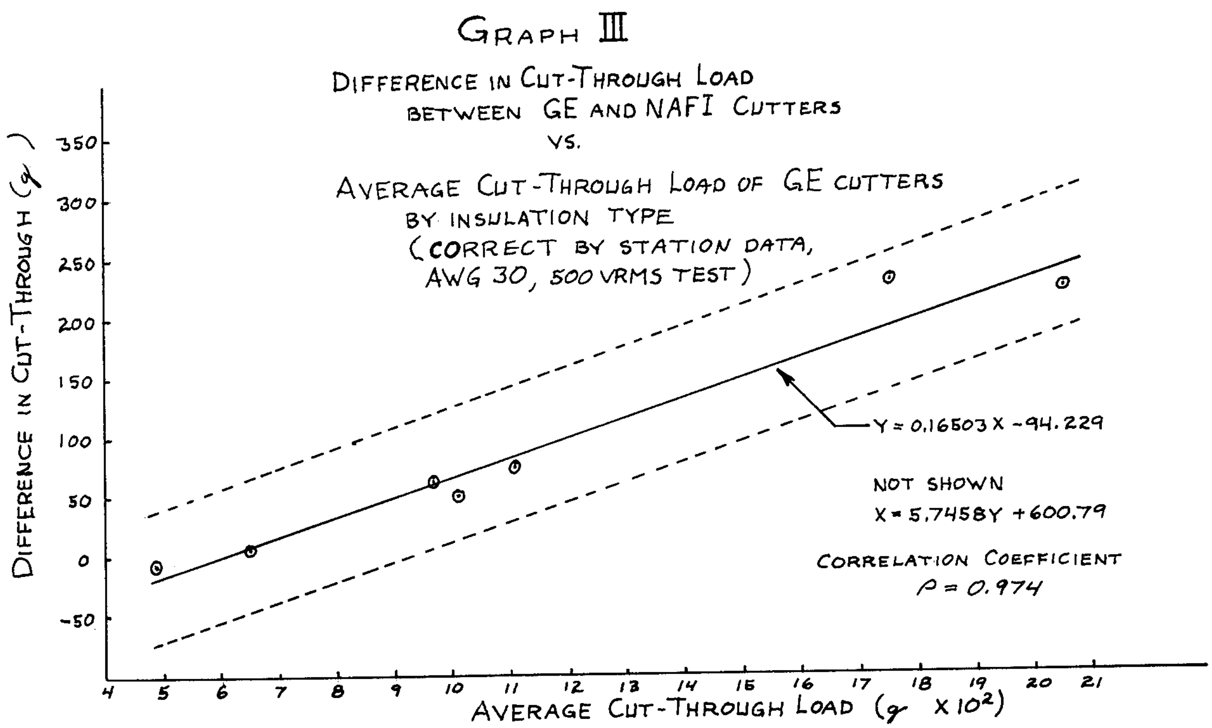


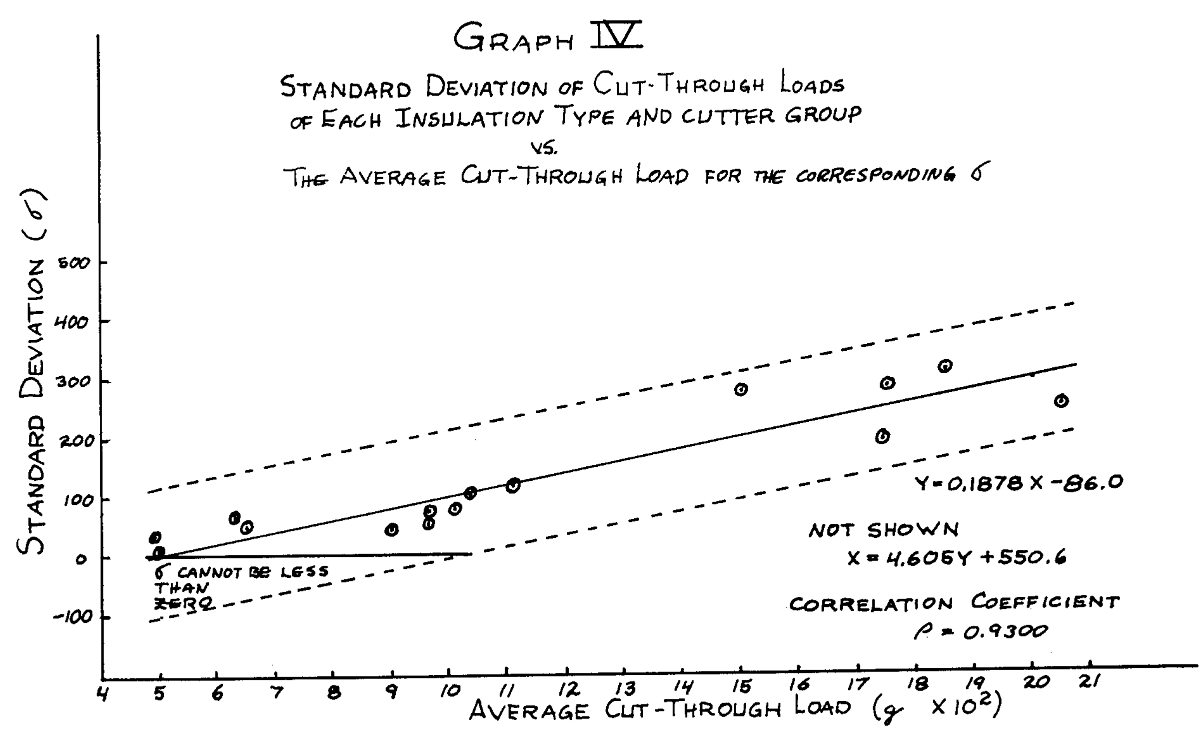
GRAPH I
AVERAGE CUT-THROUGH LOADS
AWG 30 WIRE
(SHOWING SIGNIFICANCE BY CUTTER USING PAIRED VARIATE "t" TEST)
500 VRMS TEST VOLTAGE
2000 VRMS TEST VOLTAGE
GE CUTTERS
NAFI CUTTERS
AVERAGE CUT-THROUGH LOAD (g)
TEST STATION NUMBER
1900
1800
1700
1600
1500
1400
1300
1200
1
2
3
4
5
6
7
8
9
10
YES
NO



GRAPH II
AVERAGE CUT-THROUGH LOADS
ALL AWG 30 WIRE
(SHOWING SIGNIFICANCE BY CUTTER USING PAIRED VARIATE "t" TEST)
500 VRMS TEST VOLTAGE
GE CUTTERS
NAFI CUTTERS
AVERAGE CUT-THROUGH LOAD (g)
TEST STATION NUMBER
1900
1800
1700
1600
1500
1400
1300
1200
1
2
3
4
5
6
7
8
9
10
YES
NO



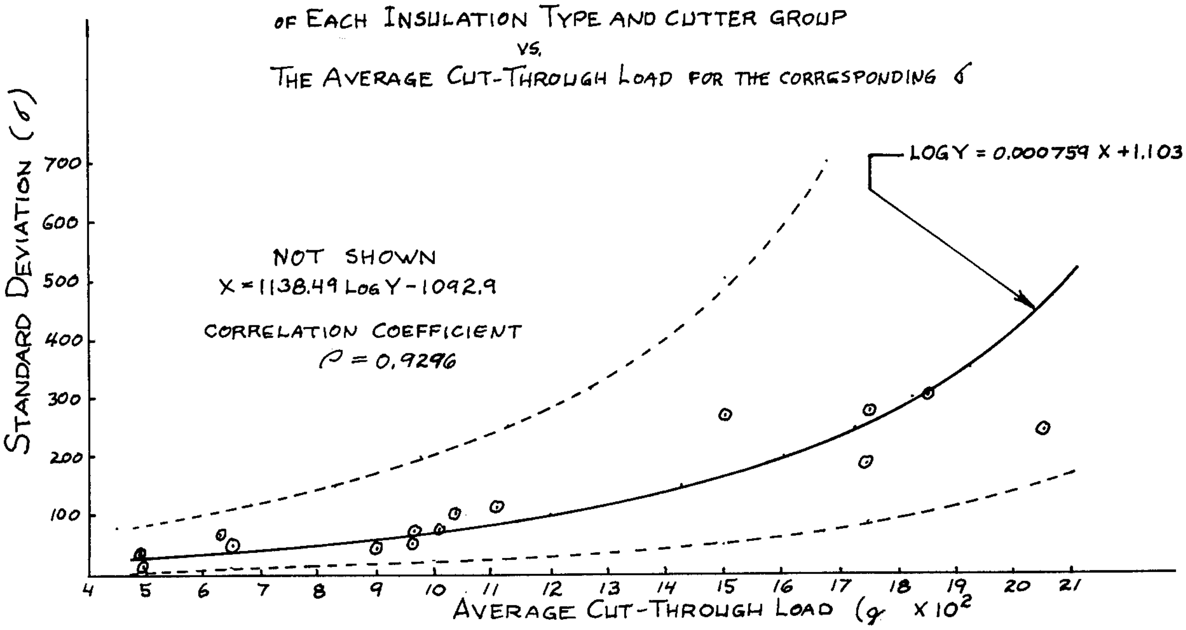
GRAPH III
DIFFERENCE IN CUT-THROUGH LOAD
BETWEEN GE AND NAFI CUTTERS
VS.
AVERAGE CUT-THROUGH LOAD OF GE CUTTERS
BY INSULATION TYPE
(CORRECT BY STATION DATA,
AWG 30, 500 VRMS TEST)
DIFFERENCE IN CUT-THROUGH (g)
350
300
250
200
150
100
50
0
-50
Y = 0.16503 X - 94.229
NOT SHOWN
X = 5.7458Y + 600.79
CORRELATION COEFFICIENT
ρ = 0.974
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
AVERAGE CUT-THROUGH LOAD (g X 10²)



GRAPH IV
STANDARD DEVIATION OF CUT-THROUGH LOADS
OF EACH INSULATION TYPE AND CUTTER GROUP
VS.
THE AVERAGE CUT-THROUGH LOAD FOR THE CORRESPONDING σ
STANDARD DEVIATION (σ)
500
400
300
200
100
0
-100
σ CANNOT BE LESS THAN ZERO
Y = 0.1878 X - 86.0
NOT SHOWN
X = 4.605Y + 550.6
CORRELATION COEFFICIENT
ρ = 0.9300
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
AVERAGE CUT-THROUGH LOAD (g X 10²)

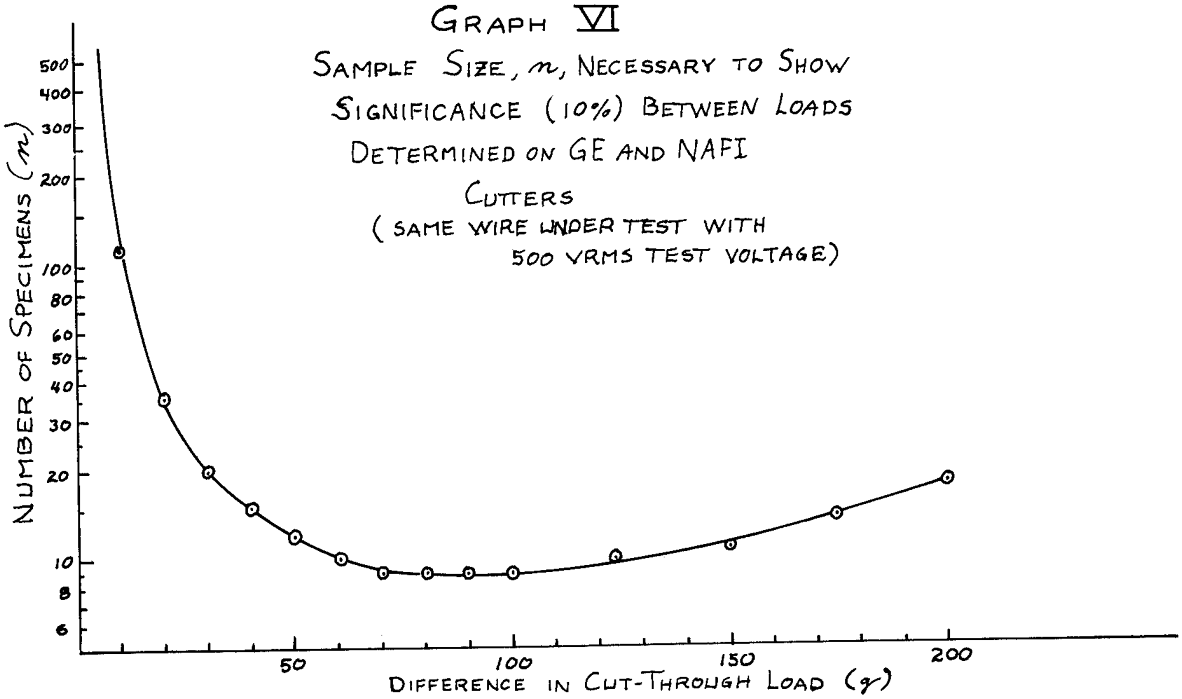
GRAPH V

STANDARD DEVIATION OF CUT-THROUGH LOADS
OF EACH INSULATION TYPE AND CUTTER GROUP
VS.
THE AVERAGE CUT-THROUGH LOAD FOR THE CORRESPONDING σ

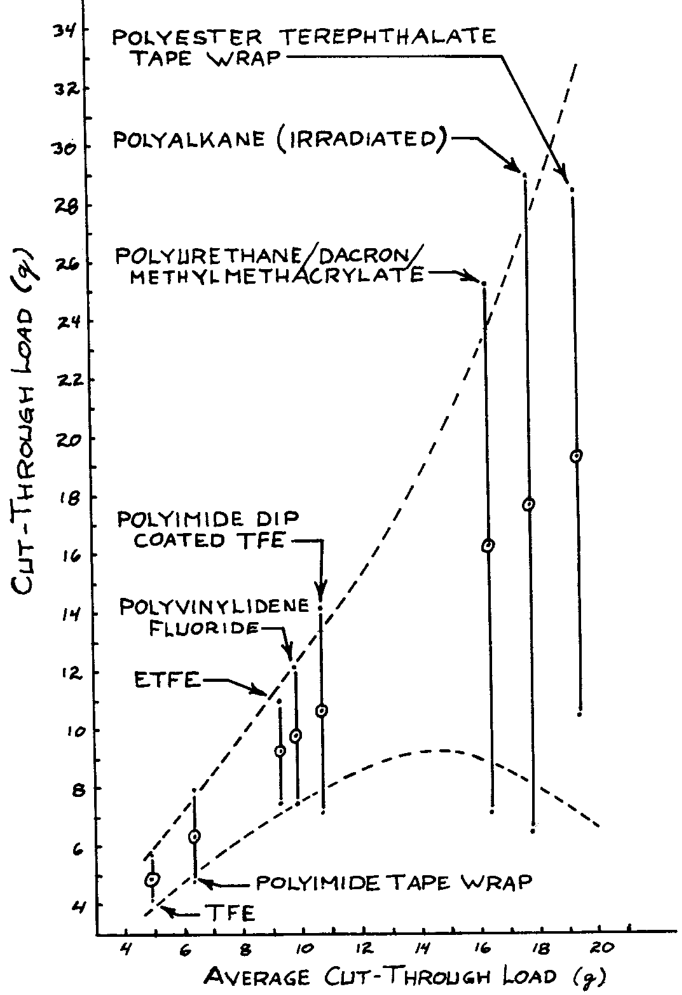


GRAPH VI

SAMPLE SIZE, n, NECESSARY TO SHOW
SIGNIFICANCE (10%) BETWEEN LOADS
DETERMINED ON GE AND NAFI
CUTTERS
(SAME WIRE UNDER TEST WITH
500 VRMS TEST VOLTAGE)



GRAPH VII
AVERAGES OF CUT-THROUGH LOADS SHOWING STATISTICAL RANGES AND THEORETICAL MAXIMUM AND MINIMUM AVERAGES, BY INSULATION TYPE, AWG 30



GRAPH VIII
DIFFERENCE IN CUT-THROUGH LOAD DUE TO DIFFERENCE IN AWG SIZE

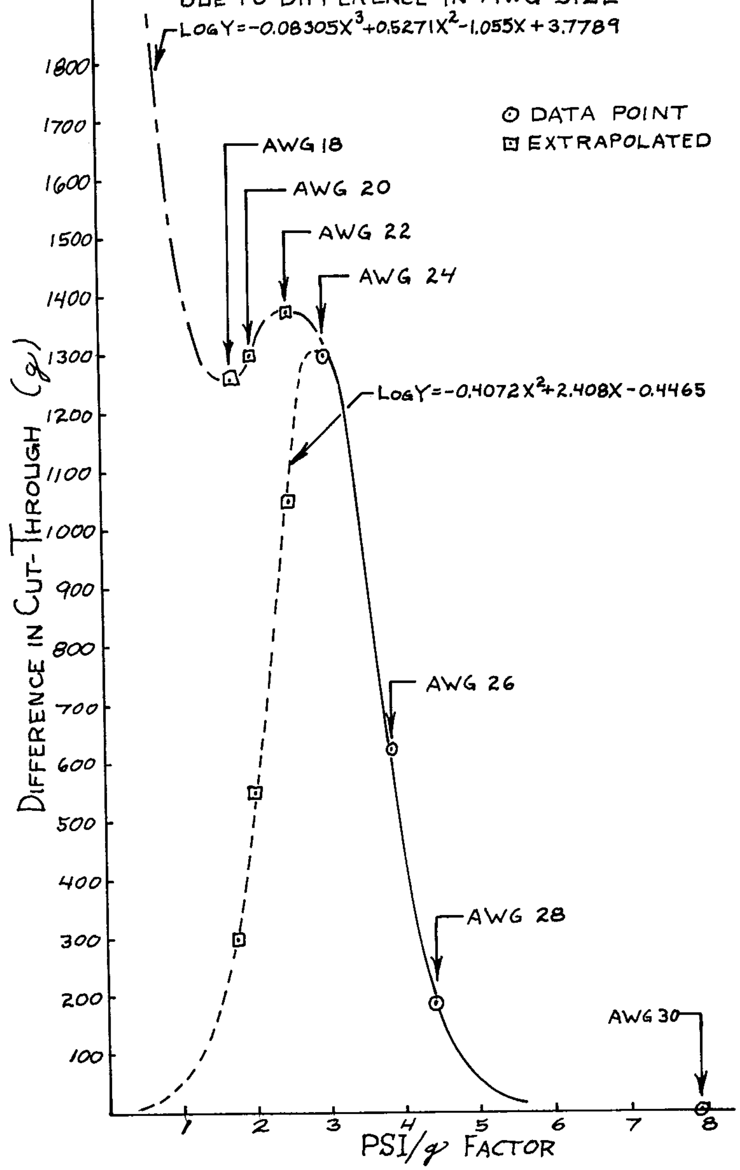


TABLE II

MASTER CHART OF CUT-THROUGH VALUES (g)

500 VRMS TEST VOLTAGE

		GE CUTTERS					NAFI CUTTERS				
		1	2	3	4	5	6	7	8	9	10
AWG 30	TFE	500	500	500	600	500	500	500	500	600	600
	Polyimide Tape Wrap	600	600	700	800	700	700	700	700	800	800
	ETFE	900	900	1000	1100	1100	900	900	1000	1300	1200
	Polyvinylidene Fluoride	900	900	1000	1000	1000	900	1100	1000	1200	1200
		1100	1100	1100	1100	1100	1000	1100	1100	1400	1400
		1100	1100	1100	1100	1100	1000	1000	1000	1500	1300
	Polyimide Dip/TFE	1100	1100	1000	1000	1000	1100	1100	1100	1400	1300
		1300	1200	1200	1300	1200	1200	1200	1200	1600	1500
	P/D/M*	1400	1400	1600	1600	1600	1500	1500	1600	2100	2000
		2100	2000	2300	2000	2000	2000	2100	2000	2300	2200
	Polyester Tape Wrap	1900	2100	2400	2700	1600	1700	1800	2200	2400	2300
		1900	2000	2200	2100	2200	1600	2200	1800	3000	3200
	Polyalkane**	1700	1600	1600	1900	1800	1500	1500	1700	2500	2800
		3800	3900	3100	3200	3500	1900	2100	—	—	2700
		2000	1700	1800	1600	2100	1500	1700	1600	3500	3400
	Polysulfone	—	—	—	—	4000	—	—	—	—	—
AWG 28	TFE	600	700	600	700	700	600	700	700	800	700
AWG 26	Polyimide Dip TFE	1000	900	1000	1100	1000	1100	1000	1200	1300	1300
	Polyimide Tape Wrap	1300	1000	1000	1100	1300	1100	1200	1300	1700	1700
AWG 24	P/D/M	2300	2300	2400	2800	2200	2200	3000	3100	3400	3000
		3000	2900	2700	2600	2800	2600	2700	2700	2900	3300
	Polyester Tape Wrap	3000	3000	3100	2700	3300	3100	2800	3700	4000	3700

2000 VRMS TEST VOLTAGE

		GE CUTTERS					NAFI CUTTERS				
		1	2	3	4	5	6	7	8	9	10
AWG 30	TFE										
	Polyimide Tape Wrap										
	ETFE	900	900	900	1000	1000	900	900	900	1200	1100
	Polyvinylidene Fluoride	800	900	900	900	900	900	1000	900	1100	1200
		1000	1000	1000	1000	1000	1000	1100	1000	1200	1200
	Polyimide Dip/TFE										
		1200	1100	1100	1200	1200	1100	1200	1100	1500	1400
	P/D/M*										
		2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
	Polyester Tape Wrap										
	Polyalkane**										
		3600	3100	3100	2900	2600	1900	2100	2600	2700	2700
		1500	1500	1500	1600	1600	1500	1600	1600	2000	1900
	Polysulfone	—	—	—	—	—	3100	—	2800	—	—
AWG 28	TFE	600	600	600	600	600	700	600	700	800	700
AWG 26	Polyimide Dip TFE	1000	900	1000	1000	1000	1000	1000	1000	1100	1100
	Polyimide Tape Wrap	1300	1000	1000	1100	1200	1100	1100	1300	1700	1400
AWG 24	P/D/M	2000	1900	2200	2400	2200	2200	2600	3100	3300	2500
		2800	2600	2700	2400	2700	2500	2700	2600	2900	3000
	Polyester Tape Wrap	2600	2800	2400	2700	2700	2600	2400	3100	4000	3300

* Polyurethane Primary insulation, Dacron Fibers, Methacrylate coated.
** Irradiated Cross-linked Polyalkane

TABLE III

CUT-THROUGH LOADS, CORRECTED, AWG 30, 500 VRMS TEST

		GE CUTTERS					NAFI CUTTERS			
INSULATION		1	2	3	4	5	6	7	8	9	10
TFE	1	500	488.5	532.2	497.7	434.3	500	507.2	481.3	473.9	507.9
POLYIMIDE TAPE WRAP	2	600	592.5	715.2	698.0	638.0	700	679.4	656.6	560.3	577.0
ETFE	3	900	904.5	964.3	998.8	1048.9	900	851.7	931.8	946.8	846.1
POLYVINYLIDENE FLUORIDE	4	900	904.5	964.3	898.8	948.9	900	1051.7	931.8	846.8	846.1
	4	1100	1112.6	1030.4	999.4	1056.2	1000	1037.8	1019.4	990.0	980.6
	4	1100	1112.6	1030.4	999.4	1056.2	1000	937.8	919.4	1090.0	880.6
POLYIMIDE DIP/TFE	5	1100	1112.6	1030.4	899.4	956.2	1100	1024.0	1007.1	933.2	815.2
	5	1300	1220.6	1096.5	1199.9	1163.5	1200	1110.0	1094.7	1076.4	949.7
P/D/M	6	1400	1424.6	1479.5	1500.2	1567.2	1500	1368.5	1457.6	1406.0	1253.4
	6	2100	2052.6	2060.8	1902.2	1992.7	2000	1899.2	1795.7	1322.2	1126.2
POLYESTER TAPE WRAP	7	1900	2144.6	2194.7	2601.6	1585.4	1700	1640.8	2032.8	1592.6	1422.5
	7	1900	2044.6	1994.7	2001.6	2185.4	1600	2054.7	1645.2	2249.3	2387.9
POLYALKANE (IRRADIATED)	8	1700	1636.6	1428.6	1801.1	1778.1	1500	1368.5	1557.6	1806.1	2053.4
	8	*	*	*	*	*	*	*	*	*	*
	8	2000	1748.6	1577.8	1501.9	2089.0	1500	1568.5	1457.6	2806.0	2653.4
POLYSULFONE	9	*	*	*	*	*	*	*	*	*	*

* NOT USED AS SOME STATIONS WERE OVER 4000 gr.

TABLE IV

STATISTICS OF GROUP DATA CUT-THROUGH LOADS, CORRECTED DATA, AWG 30, 500 VRMS TEST

INSULATION	GE CUTTERS			NAFI CUTTERS			DIFFERENCE			PROBABILITY, P, DUE TO CHANCE ALONE
	n_1	$\bar{X}_1$	σ_1	n_2	$\bar{X}_2$	σ_2	$\Delta\bar{X}$	t	df	
1	5	490.54	31.7598	5	494.10	13.9193	-3.56	-0.205	8	90% > P > 80%
2	5	648.74	49.9947	5	634.70	55.8685	14.04	0.375	8	80% > P > 70%
3	5	963.30	56.6621	5	895.30	40.8122	68.00	1.948	8	10% > P > 5%
4	15	1014.25	74.7111	15	962.13	72.0992	52.12	1.878	28	10% > P > 5%
5	10	1107.91	115.700	10	1031.03	104.4252	76.88	1.480	18	20% > P > 10%
6	10	1747.98	281.0804	10	1512.88	274.8121	235.10	1.794	18	10% > P > 5%
7	10	2055.26	248.6944	10	1832.58	306.7212	222.68	1.692	18	20% > P > 10%
8	10	1726.17	196.2165	10	1824.11	490.8496	-97.94	-0.556	18	60% > P > 50%

NOTE: X_1 BECOMES THE "X" AND $\Delta\bar{X}$ BECOMES THE "Y" OF $Y = 0.16503X - 94.229$ SHOWN IN GRAPH III, WITH THE EXCEPTION THAT 8 IS NOT USED.

INSULATION	ALL CUTTERS				
	n	$\bar{X}$	σ	$\bar{X}+3\sigma$	$\bar{X}-3\sigma$
1	10	492.3	24.583	556.0	418.6
2	10	641.7	53.478	802.13	481.26
3	10	929.3	59.957	1109.1	749.4
4	30	988.2	77.904	1221.9	754.5
5	20	1069.5	116.718	1419.6	719.3
6	20	1630.4	301.798	2535.8	725.0
7	20	1943.9	300.599	2845.7	1042.1
8	20	1776.6	376.096	2904.9	648.4

NOTE: $\bar{X}$ BECOMES THE "X" AND σ BECOMES THE "Y" IN GRAPHS IV AND V (DATA ALSO SHOWN IN GRAPH VII).

TABLE V

STATISTICS OF GROUP DATA CUT-THROUGH LOADS BY AWG SIZE, CORRECTED DATA

500 VRMS TEST

Insulation		AWG Size 30	28	26	24	$\Delta \bar{X}$	t	df
TFE	n	10	10					
	$\bar{X}$	492.3	680.0			-187.7*	-8.684	18
	σ	24.5830	60.0					
	$\bar{X}+3\sigma$	566.0	860.0					
	$\bar{X}-3\sigma$	418.6	500.0					
Polyimide Tape Wrap	n	10		10				
	$\bar{X}$	641.7		1270.0		-628.3*	-7.634	18
	σ	53.4780		241.0394				
	$\bar{X}+3\sigma$	802.1		1993.1				
	$\bar{X}-3\sigma$	481.3		546.9				
Polyimide Dip/TFE	n	20		10				
	$\bar{X}$	1069.47		1090.0		-20.5	-0.422	28
	σ	116.7180		130.0				
	$\bar{X}+3\sigma$	1419.6		1480.0				
	$\bar{X}-3\sigma$	719.3		700.0				
P/D/M	n	20			20			
	$\bar{X}$	1630.43			2745.0	-1114.57	-10.742	38
	σ	301.7980			336.8605			
	$\bar{X}+3\sigma$	2535.8			3755.6			
	$\bar{X}-3\sigma$	725.0			1734.4			
Polyester Tape Wrap	n	20			10			
	$\bar{X}$	1943.92			3240.0	-1296.08*	-9.532	28
	σ	300.5990			405.4627			
	$\bar{X}+3\sigma$	2845.7			4456.4			
	$\bar{X}-3\sigma$	1042.1			2023.6			
	PSI/g Factor	7.973	4.394	3.838	3.017			

* These values of $\Delta \bar{X}$ were used in Graph VIII.

THERMAL AGING OF TIN COATED COPPER CONDUCTORS

by

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Introduction

Tinned copper conductor is being utilized on contemporary high performance aircraft, and, in some areas, is being used in an elevated temperature environment. The maximum projected temperature is approximately 140°C (i.e., 70°C ambient temp. and 70°C rise due to resistance heating) and the total estimated time at this maximum temperature is 1250 hours. The maximum use temperature, as per the military specification, is 150°C for this wire-coating-insulation system.

The copper-tin binary phase diagram is shown in Figure 1[1]. In addition to the alpha (α) copper and the beta (β) tin there are two intermetallics in the temperature range of concern, that is, eta prime (η') Cu_6Sn_5 and epsilon (ϵ) Cu_3Sn.

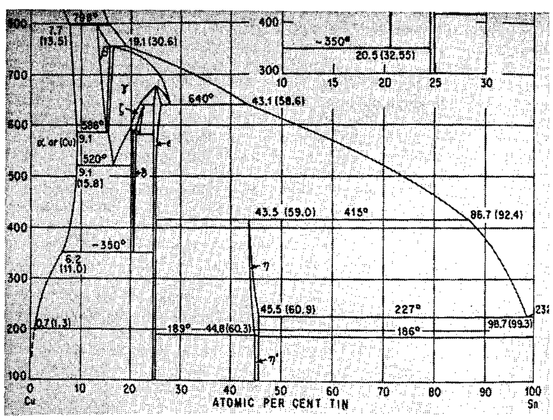

Figure 1. Copper - Tin Phase Diagram

In contrast to silver or nickel coated conductor, which is manufactured only by an electroplating process, tin coated copper may be fabricated by electrodeposition or by hot tin dipping. Such a hot dip process, as compared to an electrical plating process, yields conductor with a coating of copper/tin alloy over a core of copper. The copper/tin alloy is progressively richer in tin towards the outer surface, and the outer surface, and the outer surface is essentially pure tin. The total coating of 70 microinches normally consists of approximately 15% alloy (including both intermetallics) and 85% tin. All hot dip, tin coated conductor is received in this condition. The ratio of copper/tin alloy to essentially pure tin, in as received, hot tin dipped, insulated wire, can vary as a result of the relative 'age' of the tin bath*1, tin bath temperature fluctuations, time in the tinning bath, and elevated temperature exposures during post-tinning treatment or during the application of the insulation. The application of the insulation, wehther it be with PVC and nylon (MiL-W-5086), polyalkene and kynar (MiL-W-81044/2-15) or polyalkane-imide (MiL-W-81044/16-19), involves some elevated temperature exposure in the diffusional region. The estimated temperature of diffusional formation of each intermetallic is shown in Table 1 and is based on the empirically determined value of 55% of the absolute melting point[2]. As can be seen, will continue to form even at room temperature (on the shelf) and could become a consideration for wire which has seen a long shelf life, whereas is a consideration only for wire having seen

*1 As a tin bath is used, it picks up copper; late in its lifetime, it might have a significant copper content.

an elevated temperature exposure, either in fabrication or in service. Figure 2 shows the variation in as received wire-coating microstructure along one small segment of wire. This micrograph emphasizes the variability sometimes encountered in as received wire. Figure 3 illustrates a coating microstructure that is badly oxidized, and would indicate that in part of its processing, and most probably in the hot tinning

TABLE 1

Estimated Temperature at Which and Will Form by Solid State Diffusion*

INTERMETALLIC	CRITICAL TEMPERATURE
(Cu_6Sn_5)	2°C.
(Cu_3Sn)	106°C.

operation, the coating has seen a temperature in excess of 280°C[3], with the result that the tin has 'burned'. This, obviously, is an undesirable coating. Since tin melts at 232°C and the copper-tin eutectic alloy melts at 227°C, then, if either of these temperatures are exceeded it is quite likely that the strands of a multi strand conductor will be bonded together. This severely reduces flexibility and may adversely affect fatigue performance[4].

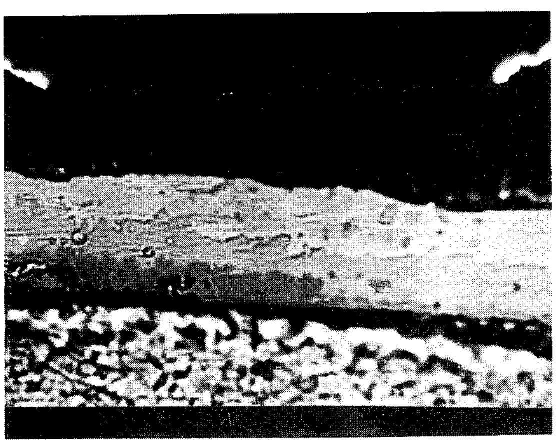

Figure 2. Micrograph Showing Variation in AS RECEIVED Intermetallic Content (1200X)

*Estimated critical temperatures for other coated copper conductors shown in Appendix 1.

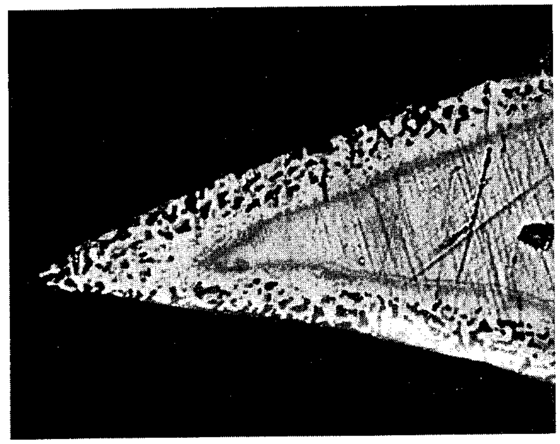

Figure 3. Oxidized Tin Coating (400X)

Electroplated tin, theoretically, should show no intermetallics at the tin-copper interface. However, as indicated in Table 1, η' will form at room temperature and above and as the electrotinning baths are normally heated to increase plating efficiency, this product too typically demonstrates both intermetallics at the Cu-Sn interface. The insulation process is a constant one, so that the intermetallics formed in this operation occur on both hot dipped tin and electro-tinned wire.

This study investigates the effect of the presence and amount of the two inter-metallic compounds on typical operational parameters of coated copper conductors to determine whether service life is shortened.

Experimental Procedure

Metallurgical Investigation: The techniques selected to monitor the metallurgical changes were X-ray diffraction, electron microprobe, and metallographic analysis. These techniques are described below:

a. X-Ray Diffraction Analysis: The X-ray diffraction measurements were made on a Picker theta-theta diffractometer with nickel filtered copper radiation. Typical power settings were 36 kV and 16 mA.

The wire samples were held in a specimen holder such that the axis of rotation of the diffractometer was parallel to the axis of the wire and coincident with the outermost surface of the wire. Every effort was made to ensure that the X-ray sampled volume was constant and any measurable differences were corrected by normalizing the data with an internal standard. In this fashion, the data may be compared on a relative basis, with a high degree of confidence, but no absolute numbers can be assumed. In order to do this, an external standard must be used, and this was accomplished by utilizing the metallographic data at three time intervals.

b. Electron Microprobe Analysis: The electron microprobe studies were made using the beam scanning technique. In this operation, an electron beam is electromagnetically deflected across the sample in both the x and y directions. An image of the area being investigated is simultaneously generated on an oscilloscope. The signal that is displayed is generated in the following manner:

First: Some of the high energy incident electrons are backscattered, the number of electrons emitted from any sample being a function of the average atomic number of the area which the beam strikes.

Second: The electrons that are captured by the object being investigated pass through it and are registered as sample current. The amount of current that will pass through any given portion of the sample is a function of its chemistry; that is, the greater the conductivity, the higher the sample current. The image generated by this method will indicate areas of different chemistries.

Third: The incident electrons striking the sample produce X-rays characteristic of the elements present, by interacting with the electronic structure of the individual atoms. The spectrometer and electronics of the microprobe are set up to receive the radiation from a particular element; when a pulse of this radiation is received, it is displayed as a point of light. The higher the percentage of an element in an area, the greater the number of dots and the closer their spacing.

c. Metallographic Examination: Samples removed from the oven were stripped of their insulation and a layer of copper was electrolytically deposited on the surface of the samples for edge preservation. The samples were then mounted and polished using standard metallographic techniques. Examination of the samples were performed with a Reichert metallograph and measurement of the thickness of any intermetallic phases and the free tin was made. Five measurements were made on each strand and at least six strands were examined for each time period.

Specimens were exposed at 135, 150, 165 and 215 ± 3°C in forced ventilation air ovens that provided an air velocity of 100 - 200 feet per minute. At each exposure temperature, the sampling periods were adjusted to yield the greatest number of data points when the measured properties were changing most rapidly. Only limited numbers of samples were exposed at 165 and 215°C as the primary emphasis was on the 150° and 135°C temperatures which were representative of the intended usage. The elevated temperature exposures are tabulated in Table 2. The time periods at 150 and 135°C were representative of maximum time at temperature projections over the lifetime of the system. The 165 and 215°C exposures were done for information purposes only and are not representative of projected usage.

TABLE 2

Elevated Temperature Exposure Spectra

Temp. (°C)	Time (Hrs.)
135	2500
150	2500
165	1750
215	150

Electrical and Mechanical Testing: As intermetallic compounds are hard, brittle, and have poor conductivity, it was necessary to determine the effect these properties might have on electrical and mechanical performance. Two situations that might be envisioned are the cracking of the intermetallics in service or on crimping and the break up

and penetration of the intermetallics when crimping aged wire(4). The questions that had to be answered were whether the cracks would propagate into the copper basis metal (Case 1) and cause a serious degradation of the electrical and mechanical performance, whether the diffusional reactions would seriously degrade the electrical performance of the conductor, or whether the embedded fragments (Case 2) would promote cracking in the copper matrix.

TABLE 3

Tests Conducted to Characterize Electro-Mechanical Behavior

Test No.	Test	AWG
1.	Conductor Resistance	14, 18 and 22
2.	Flex/Contact Resistance, Crimped Before Aging	22
3.	Flex/Contact Resistance, Crimped After Aging	22
4.	Flex/Tensile Force, Crimped Before Aging	22
5.	Flex/Tensile Force, Crimped After Aging	22
6.	Repeated Flex Life, Crimped Before Aging	22
7.	Repeated Flex Life, Crimped After Aging	22

To determine this, a series of seven electrical and mechanical tests were devised and these are listed in Table 3. The test methods are described in Appendix 2 and the purpose of each test is treated, fully, in the following section.

Experimental Results and Discussion

a. Metallographic: The results of the metallographic studies are shown in Figure 4. The results indicate that the rate of formation of the epsilon (ε) is sensitive to the variation in temperature from 150° to 135°C whereas the rate of decline of the free tin (β) is virtually the same at both temperatures. This would indicate that the β/η' interface is moving at about the same rate at both temperatures, whereas, the η'/ε front is moving at a slower rate at 135° than at 150°C. This results in more η' being formed on a relative basis at 135°C than at 150°C, before the source of free tin (β) is exhausted and the η' becomes the source for tin. The diffusional end points appear to be quite similar, as might be anticipated, however, the time sequence in reaching these endpoints is somewhat different at 135°C than at 150°C.

The diffusional sequence at 165° and 215°C occurs more rapidly than at the lower temperatures.

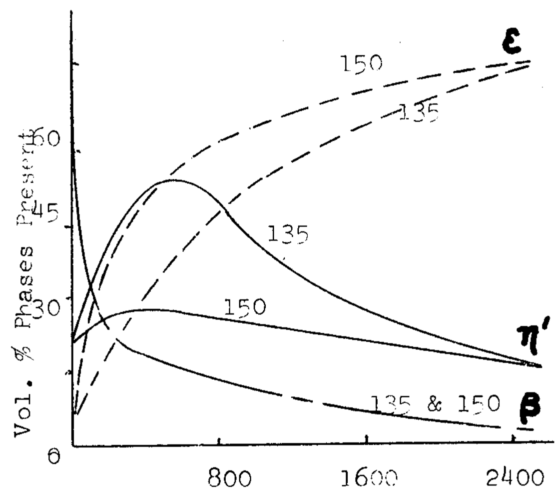

Figure 4. Percentage of Phases Present versus Aging Time

b. Electrical and Mechanical: The seven electro-mechanical tests that were conducted (see Table 3) were devised in order to determine the changes in conductor performance characteristics at both 135° and 150°C. The most basic characteristic is conductor resistance, and this was the first test conducted:

1. CONDUCTOR RESISTANCE. Conductor resistance was measured at 150°, 135°, 165° and 215°C for time periods of as long as 2500 hours, or until the performance fluctuation was seen to

stabilize. These results are shown in Figure 5 for 22AWG wire. As can be seen, the resistance increases, in all cases, to a maximum value which corresponds to approximately 4% and plateaus at this value on further aging. This is consistant with the metallographic study in that they, too, indicated a constant end point with only the time to reach this point varying. These data document the variation of reaction rate with temperature for a constant wire size (tin/copper ratio), but as the wire size diminishes the ratio of tin/copper varies (increases). It was, therefore, decided to document the effect of tin/copper ratio on the conductor resistance at both 135 and 150°C. These results are shown in Figures 6 and 7 and it is clear that the higher the tin/copper ratio the higher the percentage increase in resistance. As the 22 AWG wire is the highest tin/copper ratio in our system, this may be considered the worst case, and this increase plateaus at close to 4%, which is the value previously shown in Figure 5, for varying temperatures.

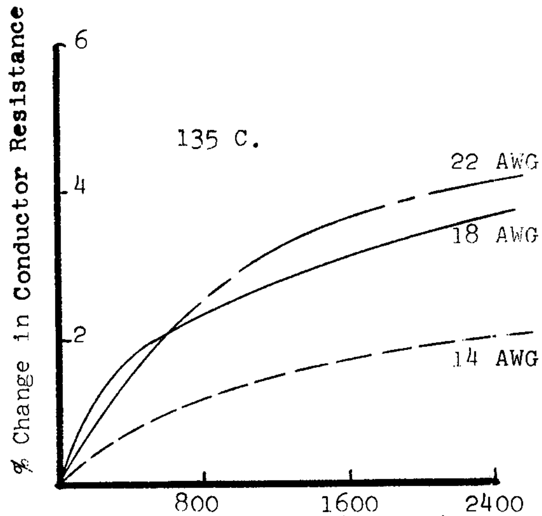

Figure 6. Conductor Resistance vs. Aging Time at 135 C.

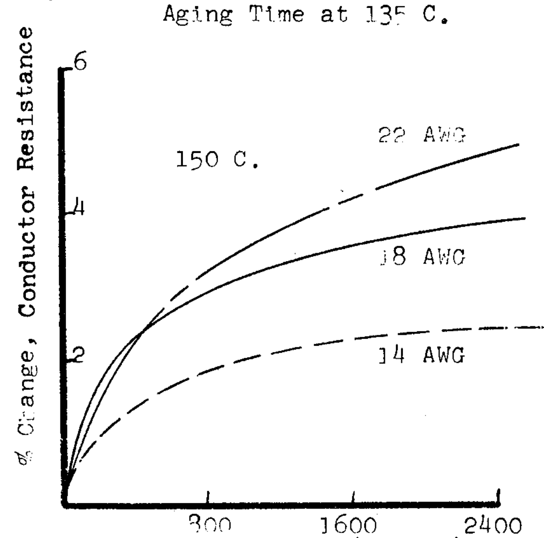

Figure 7. Conductor Resistance vs. Aging Time at 150 C.

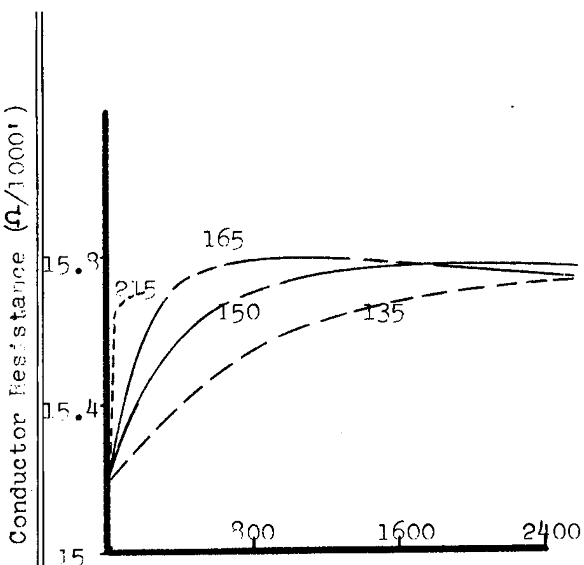

Figure 5. Conductor Resistance vs. Aging Time at 215, 165, 150 and 135 C.

2. FLEX CONTACT RESISTANCE. Flex contact resistance tests were conducted to measure the effect of the thermal aging on the crimp contact resistance. These were conducted at both 135° and 150°C with contacts assembled both before and after aging (repair simulation) and with and without wire flexing. These data are shown in Figures 8 and 9. It is clear from these data that the suspected cracks in the intermetallic layers are not seriously disrupting electrical performance. The maximum resistance increase was approximately 6.3% for contacts assembled to the wire after aging and then flexed. Although this increase is significant, it is by no means catastrophic, and may be anticipated. These results would indicate that although cracks may exist in the intermetallics due to flexing, they do not propagate into the conductor and disrupt electrical transmission, nor do any intermetallic fragments that may be embedded in the copper conductor due to crimping threaten the integrity of the conductor.

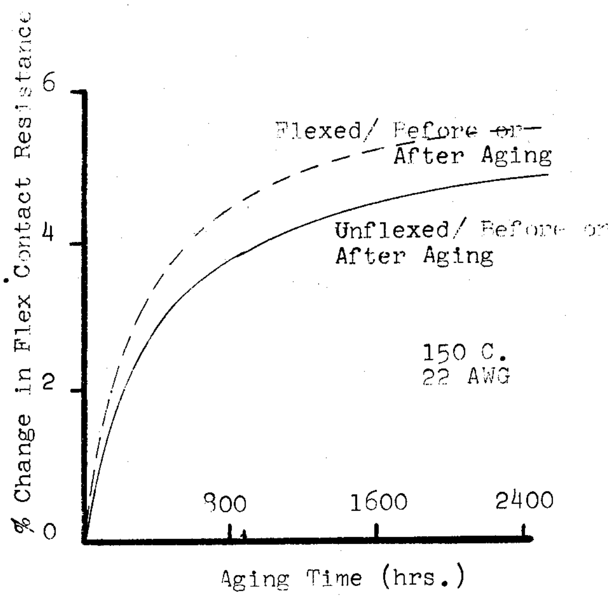

Figure 9. Change in Flex Contact Resist. versus Aging Time at 150 C.

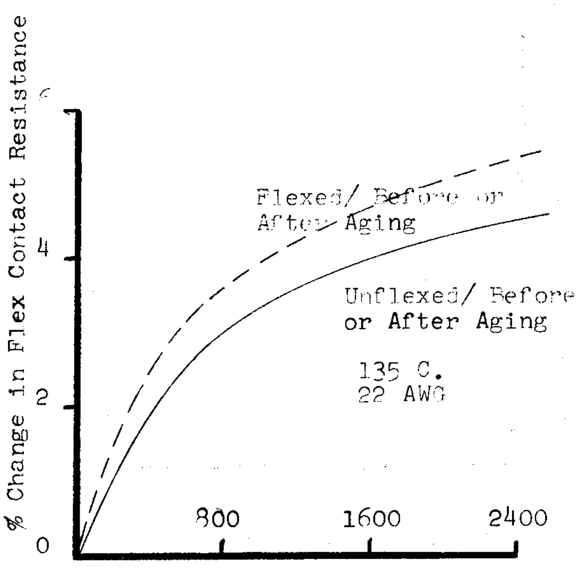

Figure 8. Flex Contact Resistance vs. Aging Time at 135 C.

Having established that the electrical integrity would be maintained, it was now necessary to determine if this was also true of the mechanical integrity. Two tests were devised to evaluate conductors exposed to both 135 and 150°C: tensile force required to fail contacts crimped both before and after aging and with and without flexing, and repeated flex life (to failure) for contacts crimped both before and after aging.

3. FLEX/TENSILE FORCE. As can be seen from Figure 10, the Flex/Tensile Force for contacts crimped before aging undergoes a significant decrease of about 20%. This drop, however, is not reflected in the contacts crimped after aging even though they had seen the same thermal lifetime. This behavior appeared to be anomolous since the decrease was initially attributed to the diffusional formation of the intermetallics. However, further investigation revealed that the decrease in tensile strength for crimped and then aged contacts resulted from the relief of the worked region in the vicinity of the crimp joint, where the failure always occurred. The flexing had an insignificant

effect on these results. To confirm that this effect was one related to the copper conductor and not to the coating system, samples of bare copper and silver coated copper wire tested. These results, shown in Figure 11, depict the same effect for both of these systems. It may therefore be concluded that this is an effect inherent to the copper conductor and true for all other copper conductor systems. The reason that the aged and then crimped wire remains unaffected is that the relieved copper conductor is reworked during the crimping operation and, hence, retains the same tensile value.

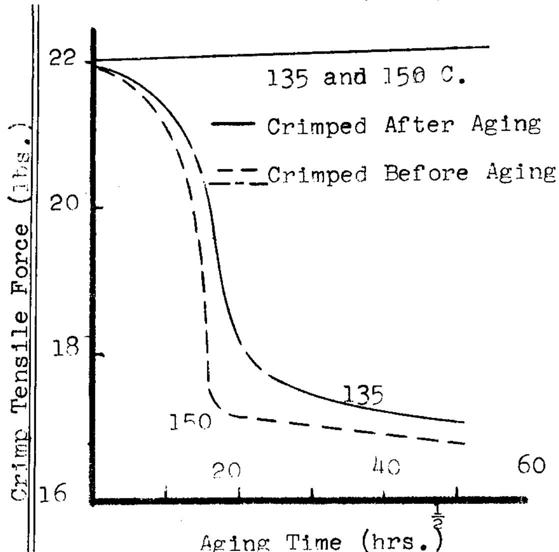

Figure 10. Crimp Tensile Force vs. the Square Root of Aging Time.

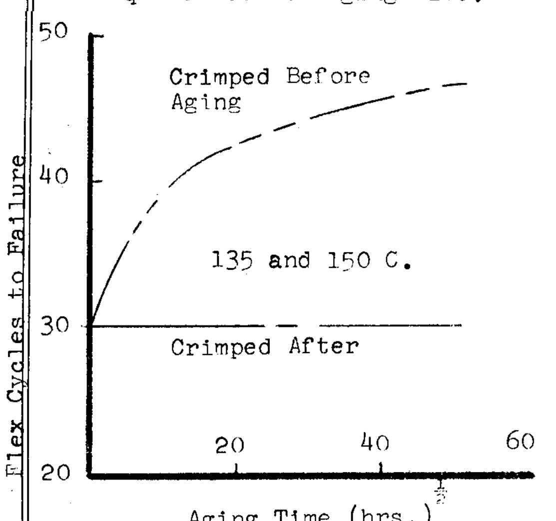

Figure 12. Flex Cycles to Failure vs. the Square Root of Aging Time

4. REPEATED FLEX LIFE. It was felt that although it had been demonstrated that a limited number of flex cycles caused no major problems with regard to electrical transmission, it was also necessary to demonstrate the same capability from a strictly mechanical standpoint. These data are presented in Figure 12. As shown, the flex lifetime for contacts crimped before aging increases and for those crimped after aging remains essentially constant. Once again, this is due to the thermal relief of the worked microstructure in the case of the crimped and aged contacts and is a result of the rework associated with the crimping operation for the aged and then crimped samples.

Conclusions

1. Conductor resistance slightly increased, and quite consistently, to a limiting value which decreased with increasing wire size.

2. Contact resistance slightly increased to a limiting value and flexing had little, if any, effect on this resistance. This fully simulated normal wire aging, normal aging with vibration and limited flexing, aged wire repair by crimping, and vibration and limited flexing of a reworked section. The increased conductor resistance accounted for almost two thirds of the measured contact resistance increase.

3. Crimped contact tensile force decreased approximately 22% for crimped and aged contacts but the decrease was found to be due to the annealing of the worked copper conductor and had no relation to the tin coating. Silver coated conductor and bare copper conductor behaved in the same fashion. This result should be incorporated into all wire system performance projections, where the copper will experience long times at elevated temperatures. Aged and then crimped samples demonstrated no change.

4. Repeated flex life increased significantly for crimped and aged contacts and this was attributed to the same thermal relief that resulted in the tensile decrease. In a fatigue or flexural environment this is decidedly advantageous.

5. Free tin was almost entirely consumed after approximately 400 hrs. at both 135 and 150°C and the solderability dropped accordingly.

6. Little, if any, oxidative degradation of the tin was found.

7. Any cracks formed in the intermetallic layers were invariably, and effectively, blunted by the copper conductor.

8. Intermetallic fragments embedded in the copper conductor did not propagate cracks in the copper basis metal.

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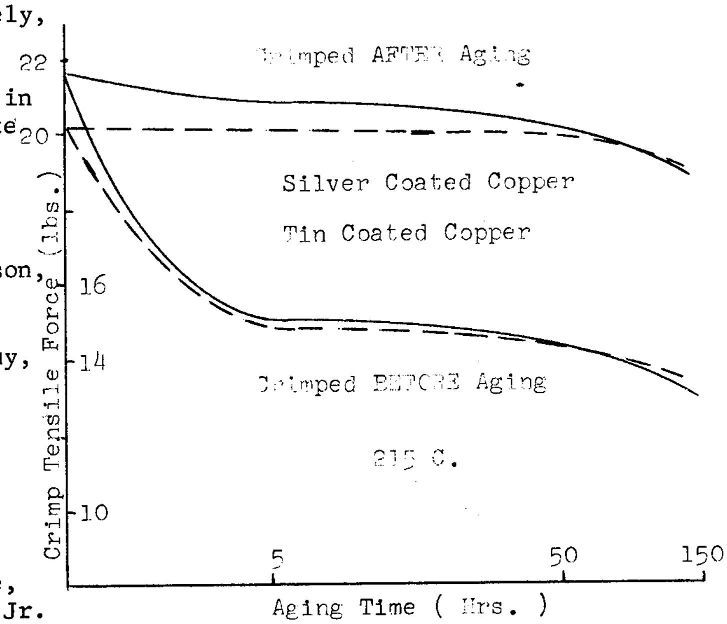

Figure 11. Crimp Tensile Force vs. Aging Time for Silver Coated and Tin Coated Copper.

APPENDIX I

Estimated 'Critical' Temperatures for Solid State Diffusion in Various Coating-Conductor Systems

SYSTEM	REACTION	CRITICAL TEMP. (°C)
Cu-Sn	$5Sn + 6Cu \quad Cu_6Sn_5$	2°C
Cu-Sn	$Cu_6Sn_5 + 9Cu \quad 5Cu_3Sn$	106°C
Cu-Ag	Eutectic (Cu + Ag)	305°C
Ag-O	$4A_g + O_2 \quad 2\ Ag_2O$	-18°
Ag-O	$2Ag_2O \quad 4Ag + O_2$	190°C
Cu-O	$4Cu + O_2 \quad 2\ Cu_2O$	463°
Cu-Ni	Eutectic (Cu + Ni)	472°

APPENDIX II

Test Methods

1. Conductor Resistance (Test No. 1)

A Kelvin Bridge was used to measure conductor resistance on specimens consisting of 50-foot lengths of wire, loosely coiled. The insulation was stripped from both ends of each specimen. At each test interval, specimens were removed from the oven and cooled to room temperature before resistance measurements were made. The same specimens were then replaced in the oven for further conditioning. The measured values were corrected to 20C using an $_{20}$ of .00392. These values were then used to calculate ohms per 1,000 feet.

Measurements were made on three specimens of each wire size.

2. Flex/Contact Resistance, Crimped After Aging (Test No. 2)

The contact resistance specimen consisted of a 6-inch length of wire with contacts applied at both ends. A Kelvin Bridge was used to measure the resistance between the positioning shoulders of the two contacts. It is recognized that this measurement includes the resistance of the 6-inch length of conductor as well as the contact resistance at both ends of the specimen. Any changes in contact resistance that are masked by the resistance of such a short length of conductor are not considered to be of functional importance.

Contacts were applied before specimens were placed in the oven. Resistance was measured on each specimen before aging, after aging, and after flexing. All measurements were made at room temperature, and the measured values were corrected to 20C using an $_{20}$ of .00392. Flexing consisted of four flex cycles, using a 45-degree deflection in both directions, with a tension load of 0.5 pounds and a flex rate of 60 flexes per minute. Both contacts on each specimen were flexed and all measurements were made on three specimens.

3. Flex/Contact Resistance, Crimped After Aging (Test No. 3)

The procedures for this test were the same as those for Test No. 2 except that contacts were applied after the wire was conditioned. Specimens were cut from loose coils of wire that were aged at the prescribed temperatures.

4. Flex/Tensile Force, Crimped Before Aging (Test No. 4)

Tensile force measurements were made on the specimens used for Test No. 2. The tensile test was performed with an Instron Tensile Testing Machine using a constant jaw strain rate of 1-inch per minute. At each test interval, one set of three specimens was tested without flexing and another set of three specimens was tested after the flexing described in 2.

5. Flex/Tensile Force, Crimped After Aging (Test No. 5)

The procedures for this test were the same as those for Test No. 4 except that contacts were applied after the wire had been aged. The measurements were made on the specimens used for Test No. 3.

6. Repeated Flex Life, Crimped Before Aging (Test No. 6)

The repeated flex life specimen was a 10-inch length of wire with a contact applied at one end. Using a 45-degree deflection in both directions and a 0.5-pound tension load, the specimen was flexed at a rate of 60 flexes per minute until all strands were broken. At each test interval, measurements were made on three specimens.

7. Repeated Flex Life, Crimped After Aging (Test No. 7)

The procedure for this test was the same as that for Test No. 6, except that the contact was applied after the wire had been aged.

A NEW FLAME RESISTANT CHEMICALLY CROSS-LINKED PVC INSULATION - FLAMENOL(R) XL

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Because of the growing need for insulation materials having improved flame resistance, General Electric has investigated many approaches for developing new insulations with superior flame-retardant properties. This undertaking resulted in the development of a versatile new chemically cross-linked PVC cable insulation, called FLAMENOL(R) XL. This material is an example of a new technology and it offers a combination of properties that is unique in the cable field today. It has allowed us to successfully introduce a new product in an old established industrial market - the wiring of locomotives and rail cars. In the future we hope to introduce a family of chemically cross-linked PVC insulations for other wire and cable applications.

Up to the present time, the longstanding practice to obtain vertical flame retardance for general-purpose thermo-setting cables has been to apply a flame-resistant material as a separate covering, such as an extruded jacket or braid, over a layer of conventional rubber insulation. For example, since its development in the late 1930's, neoprene has been widely used as a jacket to impart flame resistance to thermosetting cables. More recently, chlorosulfonated polyethylene has been used as a jacket material over ethylene-propylene rubber insulation. The primary disadvantages of applying the flame and oil flame- and oil-resistant materials as a jacket is that only a thin layer covers a relatively heavy wall of the rubber insulation and, secondly, the two layers together are larger in diameter and higher in cost than might be obtained with a single layer of a flame-retardant insulation having suitable electrical properties and mechanical toughness. Other approaches include a single-layer insulation of chlorosulfonated polyethylene which requires a heavier wall thickness, irradiated cross-linked PVC which previously has been discussed at this symposium, and flame-resistant cross-linked polyethylene insulations which generally do not exhibit the desired resistance to immersion in oil and fuels at elevated temperatures.

For our development work, PVC was a logical candidate material to fill requirements for resistance to flames and oils and to provide mechanical toughness in thin walls. PVC has a versatile combination of properties, including excellent resistance to general environmental conditions and mechanical damage, suitable electrical properties for lower voltage applications, and economical material and processing costs. In fact, the usage of PVC resin continues to grow rapidly and over 400 million pounds a year are used for extruded wire and cable applications alone. However, conventional thermoplastic PVC compositions are not suitable for many important cable applications because of deformation and flow at elevated temperatures, which occur under conditions of current overloading, short circuits, or high ambient temperatures.

I want to tell you about the program we undertook in General Electric, both at the Research and Development Center and within the Wire and Cable Department, to cross-link PVC compositions to overcome flow and deformation at elevated temperatures, thereby obtaining a physically tough thermosetting product. Faced with the challenge of developing a suitable method for cross-linking PVC insulations, we explored many avenues to obtain a material that would fulfill the wide range of performance requirements needed for rugged cable applications.

Early work was done to cross-link PVC compositions containing polymerizable monomers with high energy radiation to form a cross-linked network. A.A. Miller[1] at the Research and Development Center published the findings of this work in INDUSTRIAL AND ENGINEERING CHEMISTRY in October, 1959. This approach was not selected to fill general-purpose applications because the irradiation process was limited to smaller wall thicknesses and these irradiation cross-linked materials with plasticizers and monomers were inherently stiffer and less flexible, especially at lower temperatures.

Another approach investigated was to cross-link PVC by chemical means. The first chemical cross-linking was achieved using metal halide reagents. In September, 1965, M.M. Safford[2][3][4] received a series of U.S. patents for curing PVC with chlorides of tin, cobalt and platinum. The feasibility of cross-linking PVC by chemical means was established and work continued. In 1967, a U.S. patent[5] was issued to F.F. Holub of General Electric for curing PVC products using trioctyl trimellitates and

triallyl cyanurate in conjunction with organic peroxides. Other investigations covered chemical cross-linking of blends of PVC with other polymers, such as polyethylene, ethylene-ethyl acrylate copolymers, chlorinated polyethylene, ethylene-propylene elastomers, and others.

In the Laboratories of the Wire and Cable Department, we evaluated all approaches very carefully and carried on extensive research and development work to extend our knowledge in this field and to develop practical compounding and processing technologies. Based on a broad background, a cross-linked PVC material was selected which met the targeted property requirements. The new insulation was called FLAMENOL XL. With this material, a product line of single-wall cables having excellent resistance to flame, oil, and mechanical damage and having superior electrical properties was designed for the specific application of diesel locomotive and rail car wiring. Let us look at the unique combination of properties of FLAMENOL XL insulation and the performance characteristics of the new cable.

Cable Product Description

In Figure 1, General Electric's new single-conductor FLAMENOL XL locomotive and car cables are rated 600 and 2,000 volts and have a conductor temperature rating of 90 °C. The cables are intended for service in both ac and dc circuits and are available with flexible stranded conductors. The FLAMENOL XL product line covers a complete range of sizes from No. 16 AWG through 111 million circular mils. The locomotive cable line is commercially available today.

Diameter and Weight

Figure 2 shows a comparison of the design of the FLAMENOL XL cable to rubber-neoprene and chlorosulfonated polyethylene insulated cables. The three cables are size No. 14 AWG rated 600 volts. This is the size of the cables on which all of the data will be shown throughout the remainder of the discussion. The rubber-neoprene cable requires a 47-mil wall of rubber insulation plus a 16-mil overall jacket of neoprene for flame, oil, and mechanical protection. Chlorosulfonated polyethylene requires a single wall having 47-mil thickness. The FLAMENOL XL cable has a single wall with 30-mil thickness. For example, the overall size and weight of the rubber-neoprene cable are 150% compared to FLAMENOL XL cable. The combination of properties of the FLAMENOL XL insulation makes possible this significant reduction in wall thickness and cable diameter which is extremely important in locomotives and cars where cable channels and control compartments are very crowded and space is at a premium.

Physical Properties

In Figure 3, let us take a brief look at physical properties. Because of its two-layer construction, it is not practical to show physical property values for the rubber-neoprene cable. However, comparison of performance of complete cables will be shown for mechanical properties, before and after oil immersion, and deformation resistance. The oven aging values for the chlorosulfonated polyethylene and FLAMENOL XL insulations are very satisfactory. These two cables, when aged in a circulating air oven at 140-145 °C for 5 days showed no cracks in the insulation after wrapping around a mandrel having twice the diameter of the cables.

Continuing on Figure 4, the retention of tensile and elongation properties after immersion in ASTM No. 2 oil for 18 hours at 121 °C and in diesel fuel for 7 days at 70 °C is very satisfactory. The diesel fuel immersion test is considered to be very severe.

Mechanical Properties

Figure 5 shows the results of crushing tests between two flat plates. The results are expressed in terms of pounds force required to produce electrical failure of the insulation between conductor and ground. Results of the same test are shown after immersion of the cables in diesel fuel for 7 days at 70 °C. The FLAMENOL XL insulation with the smallest wall thickness shows superior resistance to crushing. Also, the same relative results were found when the crushing was conducted against a 3/4-inch round steel mandrel, both before and after immersion in the diesel fuel.

In Figure 6, the FLAMENOL XL insulation shows significantly superior resistance to scrape abrasion by a sharp reciprocating plunger under 3 pounds' load, both before and after immersion in hot diesel fuel.

In the test for penetration resistance shown in Figure 7, a 40-mil diameter steel wire is impressed into the insulation wall of the size 14 AWG cable under a load of 5 lbs. The FLAMENOL XL insulation shows less penetration under pressure than the other two insulations.

To summarize mechanical properties, the FLAMENOL XL insulation with reduced wall thickness is more resistant to mechanical damage than the heavier wall types. The inherent mechanical toughness of the cross-linked PVC insulation justifies the reduction in wall thickness and makes the new insulation ideally suited to resist mechanical damage and exposure to hot oils and fuels that may be

encountered in the rugged applications for diesel locomotive and rail car wiring.

Flexibility Over a Range of Temperatures

Figure 8 shows the relative torsional stiffness of slabs of representative insulation materials as measured on the Clash-Berg apparatus. The flexibility of a cable insulation should be examined not only at room temperature, but also at low temperatures that may be encountered in service.

The logarithmic chart shows that FLAMENOL XL insulation is somewhat stiffer than the other insulations at normal temperatures in the range of 20 °C (68 °F), but it does not stiffen as rapidly as the others at lower temperatures. For example, at temperatures below minus 5 °C, the chlorosulfonated polyethylene is stiffer than FLAMENOL XL. The important thing to note is that, in respect to actual bending of cables, all three materials will pass cold bending without cracking the insulation. Cold bending at minus 40 °C is satisfactory for the application.

Ozone Resistance

FLAMENOL XL and chlorosulfonated polyethylene insulations have outstanding resistance to ozone attack. To illustrate this, tests were conducted in an extremely high concentration of ozone at 0.03% conc. (30,000 parts per hundred million) at room temperature for 24 hours. The cables were bent around mandrels equal to the wire diameter. This is a very severe test where only the most ozone resistant materials withstand exposure without degradation. The FLAMENOL XL and chlorosulfonated polyethyelene insulations showed no cracking.

Degree of Cross-Linking and Deformation Resistance

The degree of cross-linking is most specifically represented by the fraction of the total polymer that is insoluble in a suitable hot solvent. For polar polymers, such as PVC, tetrahydrofuran (THF) refluxing at its boiling point of approximately 66 °C will completely dissolve or extract PVC resin. When effective cross-linking takes place, the majority of the polymer becomes insoluble and is not extractable in the hot solvent.

In Figure 9, the results of extraction of two samples having a variation in composition are shown. The tests were carried out with finely ground specimens placed in syphoning extraction cups and immersed at the refluxing temperature in fresh solvent condensing from the refluxing coils. Each extraction step was carried out for 8 hours and then the specimens were dried and weighed. This extraction step was repeated 3 times for a total of 32 hours' extraction. Note that these results show no significant change in the extraction after the initial 16 hours' period. This is indicative that a high degree of cross-linking of the insulation has taken place.

The extraction procedure was repeated on the same samples by a different procedure consisting of direct immersion of the specimens into the boiling solvent and again a consistent gel content was obtained after 16 hours.

Another index of cross-linking that may be used is the 100% modulus values measured at the elevated temperature of 150 °C. The significance of this test is that a material that is not cross-linked would be expected to have negligible at this elevated temperature and, hence, have an insignificant, low hot-modulus value. FLAMENOL XL insulation has a relatively high hot-modulus value measured at 150 °C, which is typically about 150 psi.

The resistance to deformation of the insulations on size 14 AWG cables is shown in Figure 10. The temperature is 150 °C, and the weight is 2,000 grams, which is more severe than the conditions of conventional wire deformation testing which is generally carried out at 121 °C with a weight of 500 grams. The resistance to deformation at elevated temperatures under load is excellent. FLAMENOL XL insulation compares favorably with these other thermoset insulations which are well known for their characteristically high degree of cross-linking.

To summarize, the fact that no significant extraction takes place upon repeated immersions in hot solvent indicate that PVC is intimately cross-linked in the composition. The results of hot modulus and deformation testing at elevated temperatures confirm the thermosetting characteristics of the cross-linked PVC composition.

Flame Resistance

FLAMENOL XL insulated cables pass Underwriters' Laboratories vertical flame test requirements. In addition, there is no "dripping" of flaming particles and no ignition of dry surgical cotton when placed under the flame test apparatus.

The bonfire resistance of cables in vertical trays has been tested and found to be excellent. The new cables have very satisfactory resistance to flame and fire.

Electrical Properties

FLAMENOL XL insulated cables have excellent electrical characteristics for lower voltage ac and dc applications, such as locomotive and rail car wiring. The insulation shows high voltage break-

down strength and cables are subjected to high potential testing to the standards established for thin-wall cross-linked polyethylene, which are the most stringent standards for cables in these voltage ranges. The insulation resistance of the FLAMENOL XL insulation is high and the insulation resistance constant (K) measured at 15.6 °C is typically in the range of 30,000. However, it is well known that conditions of elevated temperature and exposure to water tend to cause changes in electrical properties after prolonged periods of time. Therefore, in addition to the absolute values of electrical properties, it is important to consider the stability of electrical properties under stress.

Figure 11 shows the results of testing dielectric constant and power factor of size 14 AWG cables in water at 75 °C with 600 volts ac applied continuously during immersion for periods of 1, 7 and 14 days. The FLAMENOL XL insulation has a lower value for dielectric constant SIC measured at one day compared to chlorosulfonated polyethylene. Stability of the dielectric constant (% change in SIC from 1-14 and 7-14 days) is excellent. The stability factor, which is the difference between the power factor at 40 and 80 volts/mil measured at 14 days, also is excellent. These values are indicative of a high degree of stability for the electrical properties of the FLAMENOL XL insulation when exposed to water at elevated temperature under voltage stress for prolonged periods of time.

Figure 12 shows the results of measurements of insulation resistance in water at 75 °C with 600 volts ac applied continuously for 52 weeks. FLAMENOL XL insulation with the thinnest wall shows superior insulation resistance values compared to rubber-neoprene and chlorosulfonated polyethylene insulations.

Figure 13 shows the results of testing to determine the suitability of insulations for use on dc circuits in wet locations. This test is an electrical method for evaluating the stability of electrical properties in water at 50 °C with 600 volts dc applied negative to the conductor. This test is extremely stringent for polar insulating materials.

In this figure, the values for the dielectric constant are plotted for 52 weeks. In addition, an ac high potential of 5 kV was applied for 5 minutes to all samples without regard for wall thickness at two-week intervals throughout the duration of the test. Duration of the test normally is specified to be 16 weeks. Rubber-neoprene and chlorosulfonated polyethylene insulations tested failed the hipot test in less than 16 weeks. The FLAMENOL XL insulation with 30-mil wall thickness showed stability of the dielectric constant throughout 52 weeks.

To summarize electrical properties, the FLAMENOL XL insulation with the thinnest wall shows a high degree of stability of electrical properties in water at elevated temperatures under both conditions of ac and dc voltage applied continuously during immersion.

Conclusions

Figure 14 shows an overall property comparison of the insulations evaluated. The combination of properties of the new FLAMENOL XL insulation surpasses the other materials. Excellent resistance to flame and oil and mechanical toughness and electrical properties make possible design of new cables having a single layer of insulation material with thinner walls and smaller size.

The new FLAMENOL XL cables designed for 600- and 2,000-volt service for locomotive and rail car wiring are ideally suited to meet rigorous application requirements. It is expected that new chemically cross-linked PVC insulations will find additional cable applications in the future.

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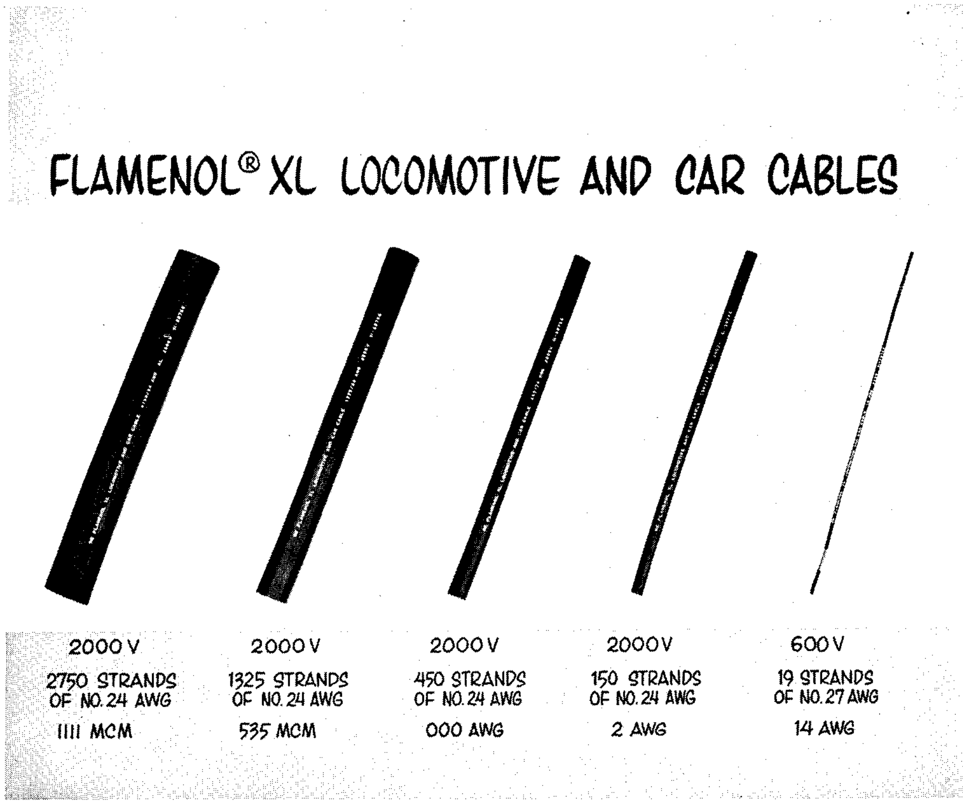
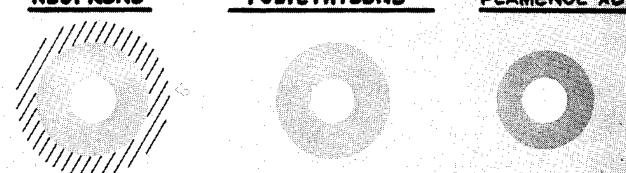


Fig. 1

DIAMETERS ... WEIGHTS

600-V NO. 14 AWG CABLES



	RUBBER NEOPRENE	CHLOROSULFONATED POLYETHYLENE	FLAMENOL XL
INSULATION WALL *(INCHES)*	.047	.047	.030
JACKET WALL *(INCHES)*	.016	–	–
MAX. DIAMETER *(INCHES)*	.201	.169	.135
INDEX FLAMENOL XL = 100	149	125	100
WEIGHT (LB./M FT.)	30	24	20
INDEX FLAMENOL XL = 100	150	120	100

Fig. 2

PHYSICAL PROPERTIES

TYPICAL VALUES - 600-V NO. 14 AWG CABLES

	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
ORIGINAL			
TENSILE (psi, min.)	—	2000	2500
ELONGATION (% min.)	—	400	200
AIR OVEN AGING			
7 DAYS @ 121 °C			
TENSILE (% ORIGINAL)	(CRACKED	90	95
ELONGATION (% ORIGINAL)	ON BENDING)	70	70
5 DAYS @ 140-145 °C			
SAMPLES WRAPPED ON 2X MANDREL	(CRACKED ON BENDING)	NO CRACKS	NO CRACKS

Fig. 3

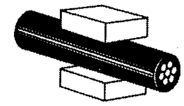
PHYSICAL PROPERTIES (CONT.)

	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
OIL RESISTANCE			
ASTM # 2 OIL			
18 HRS @ 121 °C			
TENSILE (% ORIGINAL)	—	100	90
ELONGATION (% ORIGINAL)	—	90	80
DIESEL FUEL			
7 DAYS @ 70 °C			
TENSILE (% ORIGINAL)	—	65	70
ELONGATION (% ORIGINAL)	—	95	100

Fig. 4

CRUSH RESISTANCE

600-V NO. 14 AWG CABLES

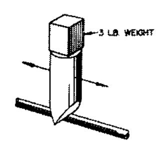


	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
POUNDS REQUIRED TO PRODUCE FAILURE FROM CONDUCTOR TO GROUND			
ORIGINAL CABLE	1000	640	2400
AFTER 7 DAYS IN DIESEL FUEL @ 70°C	170	140	260

Fig. 5

ABRASION RESISTANCE

600-V NO. 14 AWG CABLES

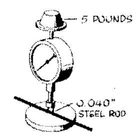


	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
NUMBER OF CYCLES REQUIRED TO EXPOSE CONDUCTOR			
ORIGINAL	700	520	2700
AFTER 7 DAYS IN DIESEL FUEL @ 70°C	10	60	130

Fig. 6

PENETRATION RESISTANCE

600-V NO. 14 AWG CABLES



	RUBBER NEOPRENE	CHLOROSULFONATED POLYETHYLENE	FLAMENOL XL
	(63 MIL WALL)	(47 MIL WALL)	(30 MIL WALL)
PENETRATION DEPTH IN MILS	64	54	19

Fig. 7

STIFFNESS IN TORSION

(ASTM D-1043)

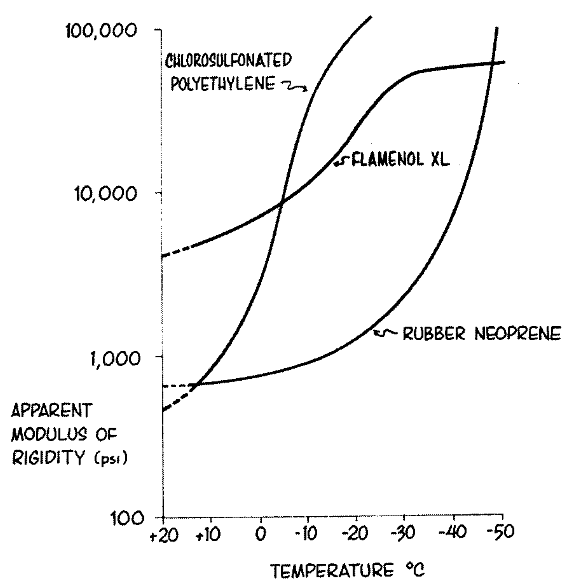


Fig. 8

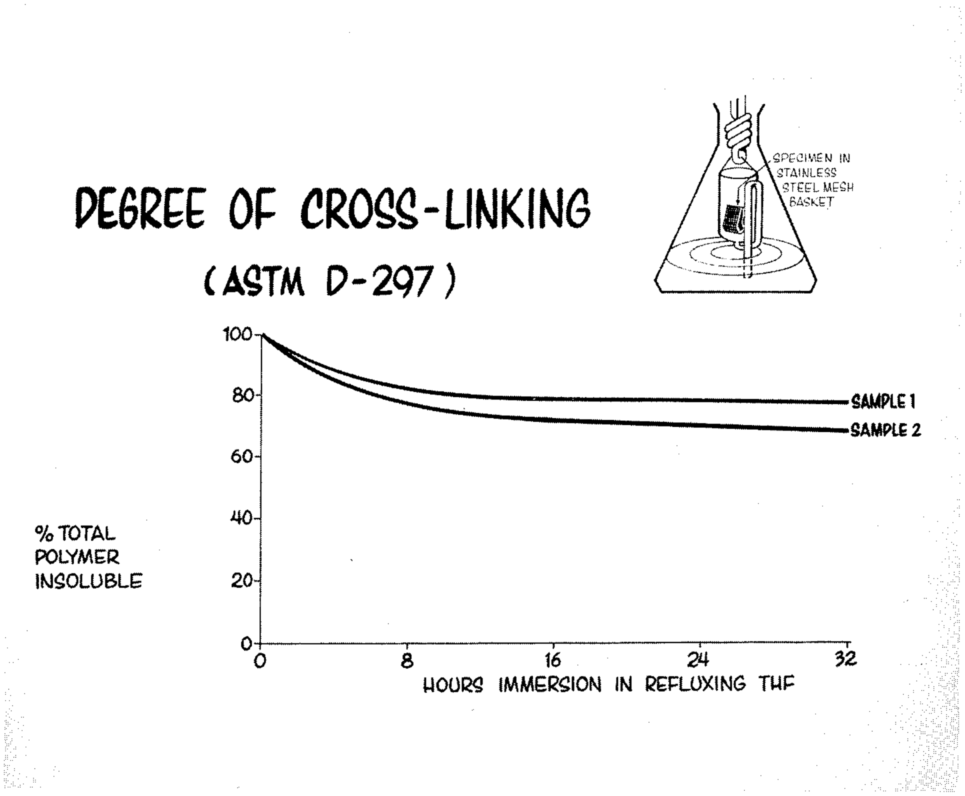
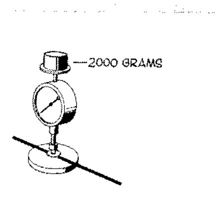


Fig. 9

DEFORMATION RESISTANCE

600-V NO. 14 AWG CABLES



	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
PERCENT OF ORIGINAL DIAMETER *(MEASURED AT 150 °C)*	71	70	**69**

Fig. 10

ELECTRICAL PROPERTIES

TYPICAL VALUES – 600-V NO. 14 AWG CABLES

	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
TEST EM-60 IN WATER @ 75 °C			
SIC (1 DAY IN WATER)	–	7.5	5.9
% INCREASE SIC			
1 - 14 DAYS	7.0	5.6	0.0
7 - 14 DAYS	-0.07	4.6	-0.17
STABILITY FACTOR	2.5	1.48	0.32
ALTERNATE STABILITY FACTOR	0.1	0.59	0.03
INSULATION RESISTANCE K FACTOR @ 15.6 °C	20,000	2,500	20,459

Fig. 11

INSULATION RESISTANCE IN WATER AT 75 °C

600-V AC APPLIED

600-V NO. 14 AWG CABLES

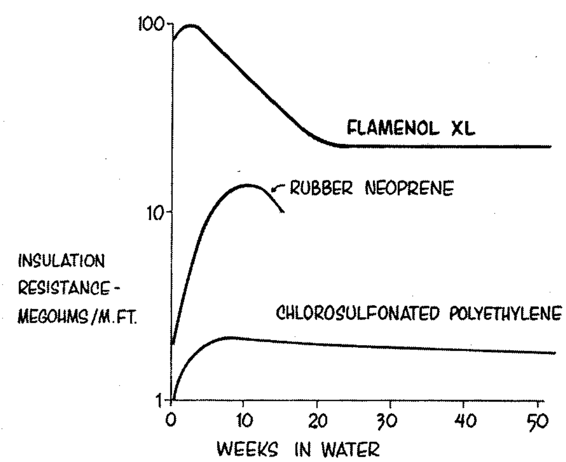


Fig. 12

MOISTURE ABSORPTION - ELECTRICAL METHOD

600 V DC NEGATIVE TO CONDUCTOR

600-V NO. 14 AWG CABLES

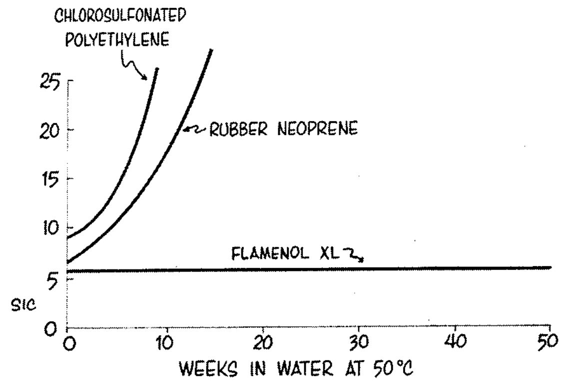


Fig. 13

OVERALL PROPERTY COMPARISON

600-V NO. 14 AWG CABLES

	RUBBER NEOPRENE (63 MIL WALL)	CHLOROSULFONATED POLYETHYLENE (47 MIL WALL)	FLAMENOL XL (30 MIL WALL)
TEMPERATURE RATING	75 °C	90 °C	90 °C
FLAME RESISTANCE	GOOD	EXCELLENT	EXCELLENT
OIL RESISTANCE	GOOD	EXCELLENT	EXCELLENT
MECHANICAL TOUGHNESS	GOOD	GOOD	EXCELLENT
FLEXIBILITY	EXCELLENT	EXCELLENT	GOOD
ELECTRICAL PROPERTIES	GOOD	FAIR	EXCELLENT

Fig. 14

J. Elwood Betts

J. Elwood Betts is a Senior Insulation Development Chemist for General Electric's Wire and Cable Products Department. His work involves the development of new insulation materials for use on GE wires and cables.

During the twenty years he has been with General Electric, he has been active in successfully developing cross-linked elastomers and plastic polymers that offer an optimum of desirable cable properties and which can be efficiently and reliably extruded under actual production conditions. At present, his special assignment is developing better flame-resistant insulations to meet applications where this is a critical property.

Mr. Betts is a graduate of Rensselaer Polytechnic Institute with a B. Chem. Engineering degree and is a member of the American Chemical Society, a Director of the Connecticut Rubber Group, and a member of the Division of Rubber Chemists, A.C.S.

He has been issued a patent in the area of chemically cross-linked ethylene polymer insulations and has several others pending.

Dr. Maurice Prober

Dr. Maurice Prober is Manager of Insulation Development in General Electric's Wire and Cable Products Department. In this position, he has, since 1961, been directly involved in the investigation and development of new GE wire and cable insulations including those in the Vulkene family which are based on chemically cross-linked polyethylene.

Prior to his present assignment, Dr. Prober was with General Electric's Research and Development Center in Schenectady, N.Y. where he carried out extensive research in the fields of fluorinated materials, silicones, high polymers and radiation chemistry. In 1958 he was appointed Liaison Scientist, responsible for implementing communications between the Research Center and General Electric operating departments.

Dr. Prober received his PHD in Organic Chemistry from Cornell University in 1946. During World War II, he served on the Manhattan Project.

Has been issued fifteen patents and is the author of twenty-six papers published and presented at technical meetings.

"MIMI", A LIGHT WEIGHT, SMALL VOLUME ELECTRICAL INTERCONNECT HARNESS FOR THE F-15

Ronald Soloman
McDonnell Aircraft Company
St. Louis, Mo.

Summary

Present and future military fighter aircraft designers must wage a constant battle against weight. Trade off studies, design evaluations, material developments, and concept analyses are continuing efforts to provide the most with the least. Today and tomorrow's trend is toward micro miniaturization, a lot with little. The electrical design engineer often finds himself with requirements to electrically interconnect numerous avionic systems and associated equipment panels and boxes after structural design is firm, armament designated, hydraulic routing completed and cooling and heating installed. Being last requires the electrical interconnect harness to be small in volume and very flexible in addition to light in weight. This is the story of development in electrical harness design at McDonnell Aircraft over the past twelve years.

Introduction

A prime consideration in the design of a weapons system is to obtain maximum capabilities with minimum weight and space penalties. The concept of "doing more with less" is applied wherever possible - most recently in electrical interconnect systems for fighter aircraft. Mimi is an acronym for Micro Miniature Compact Harnesses - the harness concept being used to interconnect the F-15 avionic systems. Let's look at how the Mimi concept was developed.

Mimi's Family Tree

Conventional

Over twelve miles of electrical wire are used in the F-4 Phantom. During early F-4 production, MIL-W-5086/2 wire with a minimum size of 22 AWG was used. This wire had a 22 mil insulation wall and weighed 4.70 pounds per 1000 feet. This electrical wire harness was so large that installation and repair proved difficult.

Compact

A search for new materials and techniques resulted in the selection of MIL-W-22759, MS21985 wire with a 10 mil insulation wall weighing 3.72 pounds per 1000 feet for 22 AWG (still minimum wire size). A braided dacron polyester protective jacket was used to encapsulate the harness to provide abrasion and cut through protection not afforded by thin wall insulated wire. This configuration was called a Compact harness and has been used on over 4200 F-4's.

Minicomp

As the F-4 expanded its avionic capabilities, more and more wire was crowded in the Compact harness. By 1966, it was apparent that another look at electrical harness systems was needed. The interconnect harnesses were again becoming difficult to install and maintain. In 1968, a Minicomp (for miniature compact) harness using MIL-W-81381/1 and /5 wire with a seven mil insulation wall and weighing 1.5 pounds per 1000 feet for 26 AWG (new minimum wire size) was used to interconnect the Loran D avionics system and for instrumentation interconnect on several flight test aircraft. Combined with a new miniaturized polyimide fluorocarbon coax that was developed, a significant weight and volume reduction was achieved with Minicomp.

Mimi

In 1969 it became mandatory to develop an electrical interconnect harness with still lower weight and space requirements while maintaining high reliability and ease of installation and repair. This demand was exacted by the design competition for the contract award on the Air Force F-15 air superiority fighter. Mimi was developed and tested during this time. Mimi incorporated the latest developments in conductors, insulation and connector concepts. Mimi features:

- 24 and 26 AWG high strength alloy 135 conductors
- All conductors with unilay stranding for minimum diameter and weight and optimum stripability
- 5 mil minimum polyimide fluorocarbon insulation wall with polyimide topcoat
- Color coded hookup wire and cable for easy gauge size identification
- Multiconductor cable band coded for conductor identification
- Subminiature, environmentally sealed connectors with high density pin spacing
- Braided polyester protective harness jacket.

Connectors

The subminiature, environmentally sealed connector offers considerable weight and space savings when compared to the standard miniature connector. Figure 1 compares a 21 pin coax connector and a 98 pin rectangular connector of both versions. The subminiature connectors also have the advantage of a smaller hand envelope for access.

Weight and Space Comparison

Figure 2 depicts the four generations of harness development at MCAIR. The harness shown is a Forward Looking Radar Harness used on the RF-4C and built to the four concepts previously discussed. Each harness has 9 connectors and 200 wires. The following weight and cross sectional areas were measured.

Config.	Weight (lbs)	New Weight	Cross Sect. Area (Sq. In.)	New C.S.A.
1959	24.81		1.044	
1960	22.00	88.6%	0.773	70%
1968	11.34	45.7%	0.308	30%
1971	9.60	38.7%	0.246	24%

Maintainability Record

Several recent maintainability studies were conducted to determine the mean time between maintenance action (MTBMA) and the maintenance man hours per flight hour (MMH/FH) for compact harnesses versus conventional open laced harnesses. Figure 3 shows that the F-4 with the compact harness has more than double the mean time between maintenance action of its nearest competitor (DC-8). Figure 4 illustrates that the Compact harness of the F-4 has a very respectable maintenance man hours per flight hour record although not as good as some commercial aircraft.

A distinct maintenance advantage of the braided harness is that it may be removed, repaired and reinstalled as an entity. During retrofit, an entire harness may be removed for modification without affecting the integrity of adjacent harnesses.

Distinctive Manufacturing Techniques

AWG Size Code

To minimize confusion and errors between AWG sizes, an AWG size code has been chosen to provide easy identification of wire AWG. This size code will be used on hookup wire, airframe wire and cable. The wire insulation will be of a solid color for conductor AWG identification. The color - AWG size code selected conforms to the colors already established for identifying terminals and connector contact pins as specified in MIL-C-23216, 26636, 39029 and MIL-T-7928. A tabular listing follows:

26 AWG - Black	18 AWG - White
24 AWG - Blue	16 AWG - Blue
22 AWG - Green	14 AWG - Green
20 AWG - Red	12 AWG - Yellow

Cable Conductor Code

Since solid colors have been selected for AWG size identification, another approach was needed (other than helical color stripes or solid colors) to identify conductors within a multiconductor cable. A circumferential band code was chosen as being the easiest to identify with a solid color background. The number of bands represent the conductor number except for conductor one which is not band coded. See Figure 5.

Wire Identification

Circuit identification is achieved by installing a circuit identified thermofit shrink sleeve at each terminated wire end. Subsequent application of heat to the sleeve shrinks it down on the wire. Placing the sleeve between the thumb and forefinger and exerting a pulling or pushing force parallel to the wire permits the sleeve to be moved to its proper orientation in final harness operations. This approach when compared to printing the circuit identification on the wire offers decreased costs, faster repair, replace or retrofit of wires in a harness and elimination of printing problems normally associated with small size 24 and 26 AWG wires. It has the disadvantage of not providing wire identification between terminated ends and not being an accepted procedure per MIL-C-5088.

Connector Strain Relief

A connector strain relief evaluation investigated standard connector strain reliefs, Glenair Qwik Ty, molded shrink boots and a molded cone. The molded cone was selected for final qualification testing because of its low cost, easy assembly and repair, weight savings, added wire and grommet protection and good performance in torsional and flex tests. Figure 6 shows an early developmental molded cone strain relief in comparison to a standard strain relief.

Harness Twist

Flexibility during harness installation in the airframe is vital. A stiff harness provides undue hardships when installing, repairing or removing. To increase harness flexibility, specified random twist is employed. The wires are formed, combed, twisted and taped as illustrated in Figure 7.

Harness Braid

An open harness uses a wire with sufficient insulation toughness and thickness to provide its own mechanical abrasion protection. In contrast, a braided harness uses a thin wall insulated wire (commonly referred to as hook up wire) and achieves mechanical abrasion protection by over-braiding the completed harness. A black, polyester yarn is the braid material used on all standard MCAIR harnesses. New England Butt Braiders with 24, 32, 48 and 64 carriers apply the spooled polyester yarn (1100 denier, 250 strand). For high temperature harnesses (to 260°C), nylon yarn is used.

Some harnesses either radiate or are susceptible to electromagnetic interference (EMI). When shielding of the individual wires proves inadequate, the entire harness may be shield braided. Ninety percent shield coverage is required. A 33 AWG, tin plated copper, four or eight ends per spool, is the shield material used at MCAIR. Polyester yarn will be braided over the shield as a final protective jacket. Figure 8 demonstrates a typical braiding operation.

Jacket Topcoat

After the protective jacket braiding is complete, the harness is placed on a metal screen above a tank filled with topcoating solution. A container is used to pour the solution over the braided harness and the metal screen permits the excess to drain back to the tank. After application of the solution to the protective jacket, a forty eight hour air dry is necessary before the harness can be bagged and sealed for storage. The harness can be moved and worked after approximately two hours. The topcoat bonds the yarn strands, minimizes fraying that is associated with untreated yarns and improves the moisture resistance. Monochlorotrifluorethylene (Kel F) is used on the polyester yarn and synthetic elastomer (Viton) on nylon yarn.

Conductor Current Ratings

With the development of new, high temperature insulations, increased current ratings are possible for conductors. After comprehensive laboratory testing of single wire and harness configurations, new current ratings were established based on the maximum total continuous temperature allowable for the insulation and conductor. These ratings are applicable to both Teflon and Kapton insulated conductors for F-15 applications. The tests were based on a 37 wire harness with 7 of the wires carrying full test current and the other 30 wires carrying 0.25 amperes. The MCAIR ratings are for 150°C ambient, sea level.

	Current Rating - Amps	
	Single Wire	
Conductor	5088D	MCAIR
26 AWG Alloy	-	7
24 AWG Alloy	-	9
22 AWG Copper	-	14
20 AWG Copper	11	20
18 AWG Copper	16	26
16 AWG Copper	22	32
14 AWG Copper	32	43
12 AWG Copper	41	53

	Current Rating - Amps	
	Harness Wire	
Conductor	5088D	MCAIR
26 AWG Alloy	-	4
24 AWG Alloy	2	6
22 AWG Copper	5	9
20 AWG Copper	7.5	12
18 AWG Copper	10	16
16 AWG Copper	13	20
14 AWG Copper	17	25
12 AWG Copper	23	32

A comparison of the harness wire rating of MIL-C-5088D and MCAIR shows that a smaller gauge size conductor can be used where current rating is the determining factor. This can be a major factor in contributing to the overall weight and volume reduction of an electrical harness.

Shield Braid on Cable

MIL-C-27500 requires a 36 AWG shield braid on .061 to .310 inch cable diameter. F-15 shielded cable evaluation has shown 38 AWG braid to have equal shielding effectiveness on up to .250 inch cable diameter. With the use of increasingly complex and sophisticated avionic systems on fighter aircraft, more and more shielded cable is required to protect the sensitive circuits. By reducing the shield strand size to 38 AWG for up to a .250 inch cable, shielding weight is minimized without reducing shielding performance.

Design Applications

Provided with 24 and 26 AWG conductors, thin wall insulation, higher current ratings and reduced size shield braid, the design engineer has the potential to create a light weight, small volume, high reliability electrical interconnect harness. Now, as never before, the engineer must know currents for each circuit, circuits where voltage drop requirements are critical and sensitive or radiating circuits that require shielding. The developments in wiring materials and concepts

can only be effectively utilized if the design engineer is acutely aware of the circuit requirements of his avionic systems. Only through excellence in design can the optimum electrical harness be achieved.

F-4 vs F-15

The Mimi harness for the F-15 offers numerous design improvements over existing compact harnesses used on the F-4. They are:

- o Lighter Weight and Smaller Volume

  24 and 26 AWG unilay conductor

  Thin wall insulated wire

  38 AWG shield braid

  Higher current ratings

- o Reduced Manufacturing Operations

  Minimized use of etched wire and potted connectors

- o Easier Installation and Removal from Aircraft

  Smaller harness volume improves flexibility and accessibility

- o Improved Maintainability

  Easy access to wire and terminals in connector grommet area

- o Enhanced Survivability

  Reduced harness volume and rugged polyimide insulation

Conclusion

The electrical harnesses for the F-15 employ the latest development in:

- o Small gauge conductors
- o Conductor stranding
- o Thin wall insulation
- o High density connectors
- o Connector strain reliefs
- o AWG code identification
- o Cable code identification
- o Shield gauge size and
- o Wire current ratings

to insure a light weight, small volume, highly reliable interconnect system. The electrical design engineer has the capability of "doing more with less" assuring maximum design with minimum weight and space penalties, thanks to Mimi.

Ronald Soloman graduated from Washington University in 1956 with a BSEE. After two years with the U. S. Army as a radar and guided missile instructor, he joined the Emerson Electric Company of St. Louis. He worked as a calibration and test engineer on the B-52 and B-58 Radar Fire Control Systems. After coming to McDonnell Aircraft Company in 1964, he has worked as an engineer in the Avionics lab, electronic systems and design engineering. He presently is a member of the electrical design staff involved with improved methods of electrical interconnect.


Weight and Space Reduction by MIMI
Connector Miniaturization
MIMI
COMPACT

FIG. 1

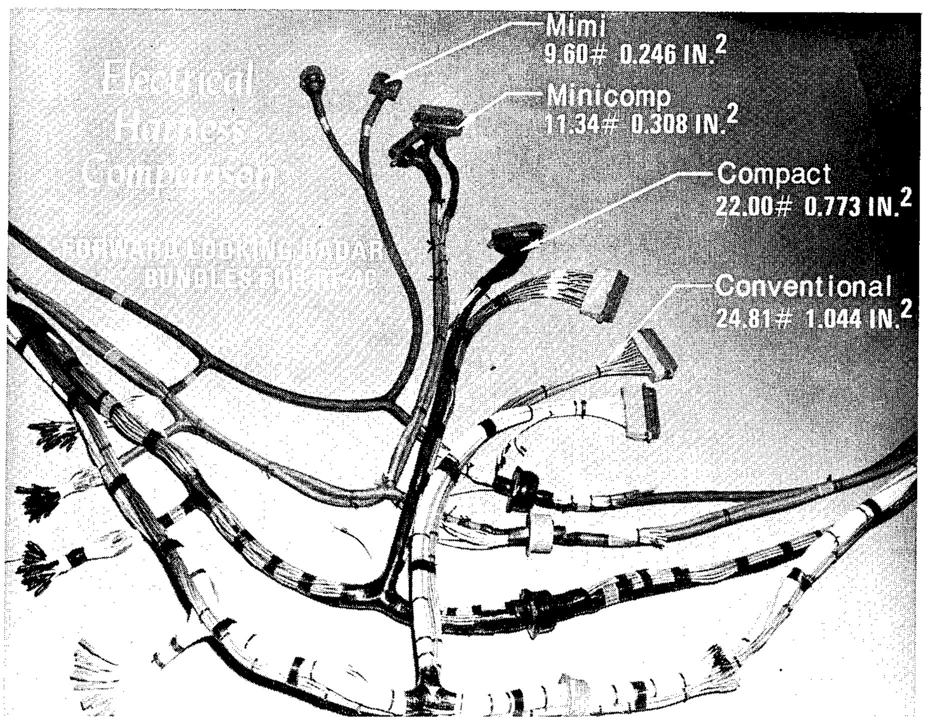
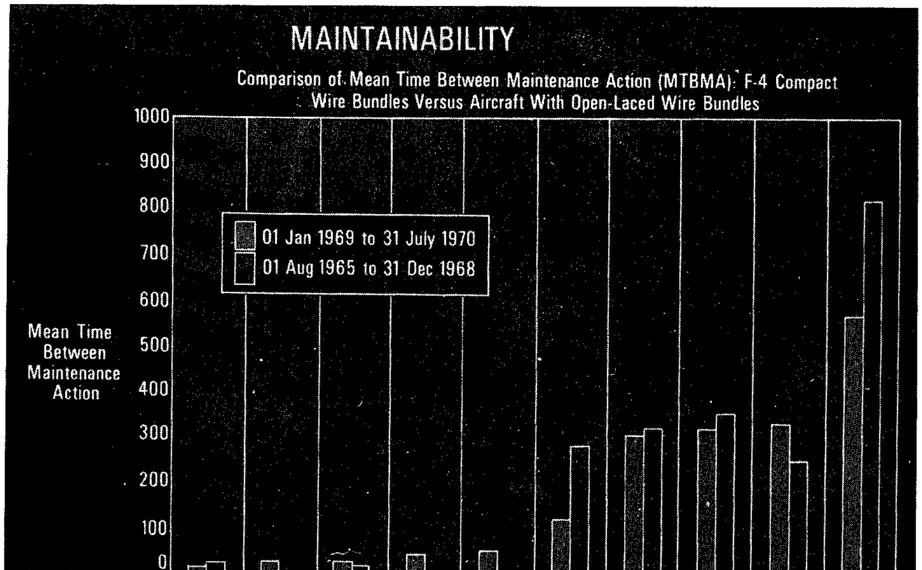
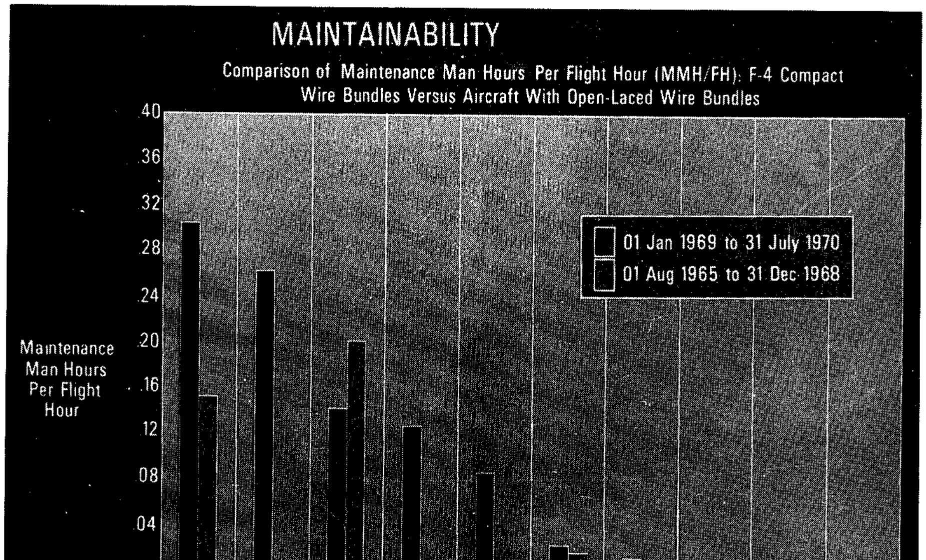

Electrical Harness Comparison
FORWARD LOOKING RADAR BUNDLES FOR RF-4C
Mimi
9.60# 0.246 IN.^{2}
Minicomp
11.34# 0.308 IN.^{2}
Compact
22.00# 0.773 IN.^{2}
Conventional
24.81# 1.044 IN.^{2}

FIG. 2



Type Aircraft	F-105B/D	A-6A/B/C	F-106A/B	A-7D	T/A-4A/B/C/E/F/J	B-720	B-737	DC-8	B-727	F/RF-4B/J
MTBMA	5.0	21.4	27.2	35.1	50.6	130.6	304.2	322.1	328.5	655.9
MTBMA	13.0		21.1			278.1	314.9	342.8	258.9	813.0
FH BASE	26356	8013	30999	3160	290184	39180	110103	356634	409006	194807
FH BASE	107366		56425			49772	26448	155995	163895	208952

FIG. 3



Type Aircraft	F-105B/D	A6-A/B/C	F-106A/B	A-7D	T/A-4A/B/C/E/F/J	B-720	F/RF-4B/J	DC-8	B-737	B-727
MMH/FH	.30943	.18672	.14071	.12275	.08198	.01982	.01013	.00647	.00635	.00439
MMH/FH	.15903		.19937			.00769	.00830	.00643	.00520	.00520
FH BASE	26356	8013	30999	3160	290184	39180	194807	356634	110103	409006
FH BASE	107336		56425			49772	208952	155995	26448	163895

FIG. 4

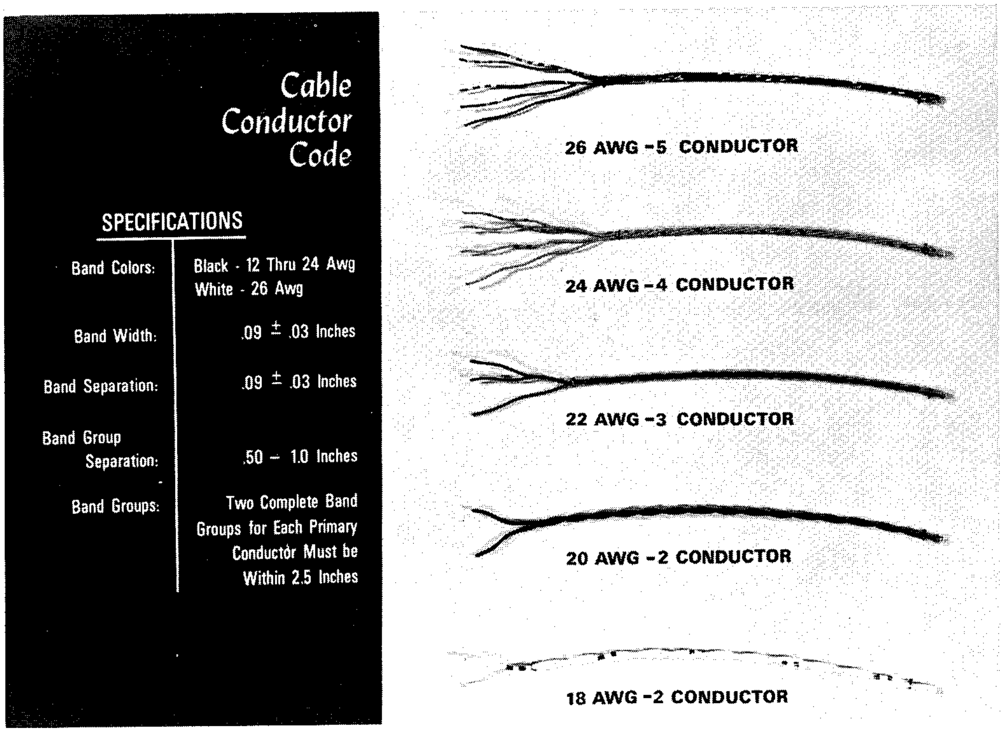

Cable
Conductor
Code
SPECIFICATIONS
Band Colors:
Black - 12 Thru 24 Awg
White - 26 Awg
Band Width:
.09 ± .03 Inches
Band Separation:
.09 ± .03 Inches
Band Group
Separation:
.50 – 1.0 Inches
Band Groups:
Two Complete Band
Groups for Each Primary
Conductor Must be
Within 2.5 Inches
26 AWG -5 CONDUCTOR
24 AWG -4 CONDUCTOR
22 AWG -3 CONDUCTOR
20 AWG -2 CONDUCTOR
18 AWG -2 CONDUCTOR

FIG. 5

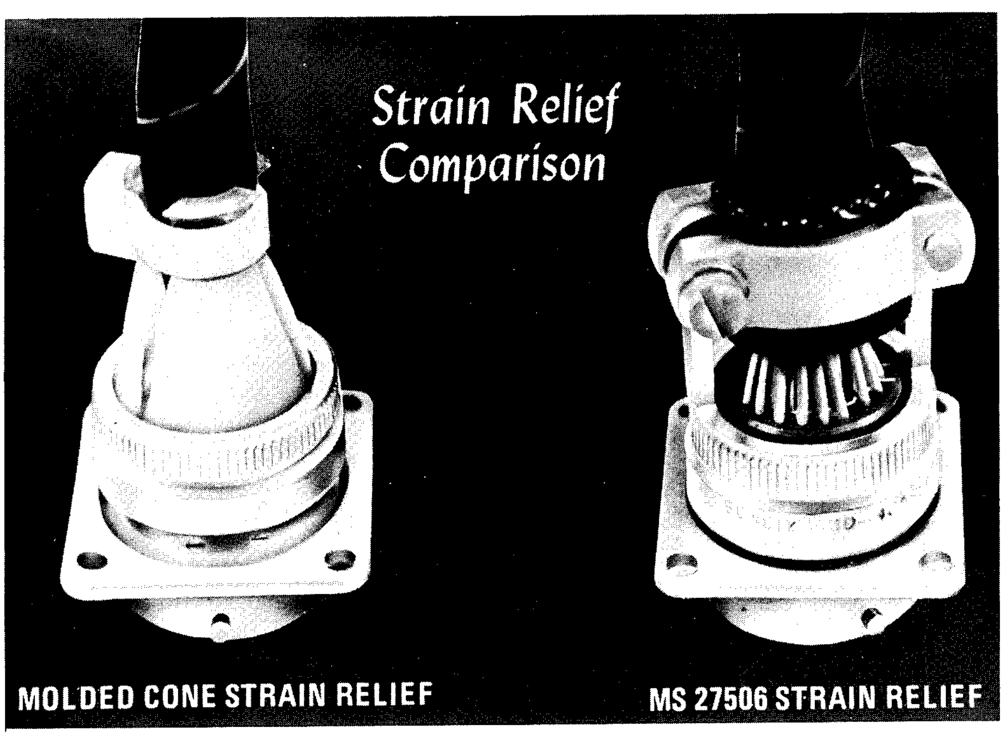

Strain Relief
Comparison
MOLDED CONE STRAIN RELIEF
MS 27506 STRAIN RELIEF

FIG. 6

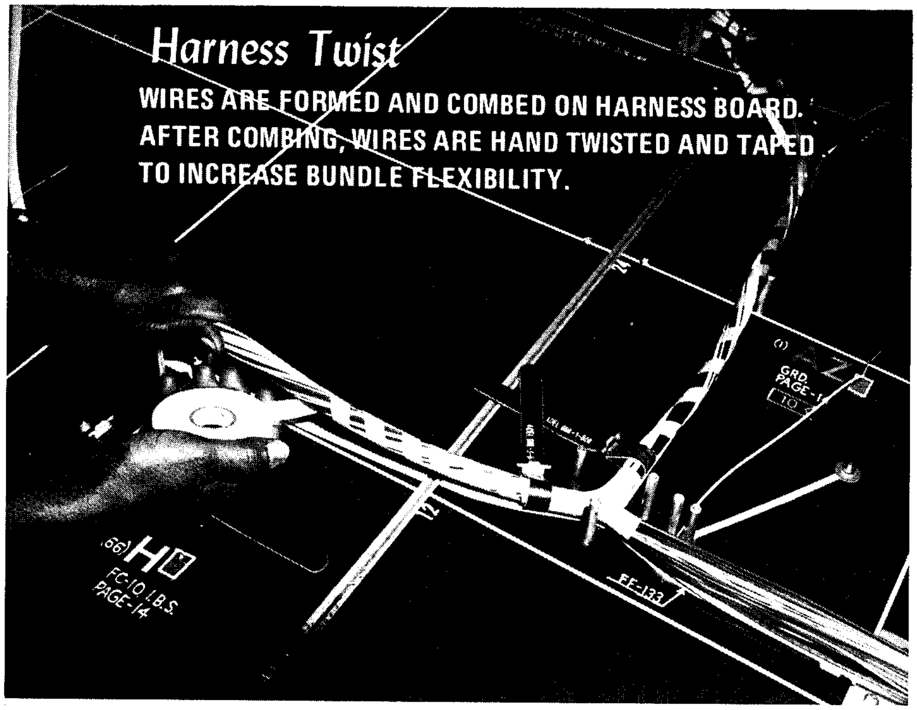

Harness Twist
WIRES ARE FORMED AND COMBED ON HARNESS BOARD.
AFTER COMBING, WIRES ARE HAND TWISTED AND TAPED
TO INCREASE BUNDLE FLEXIBILITY.
GRD.
PAGE-1
10
FC-10 L.B.S.
PAGE-14
FE-133

FIG. 7

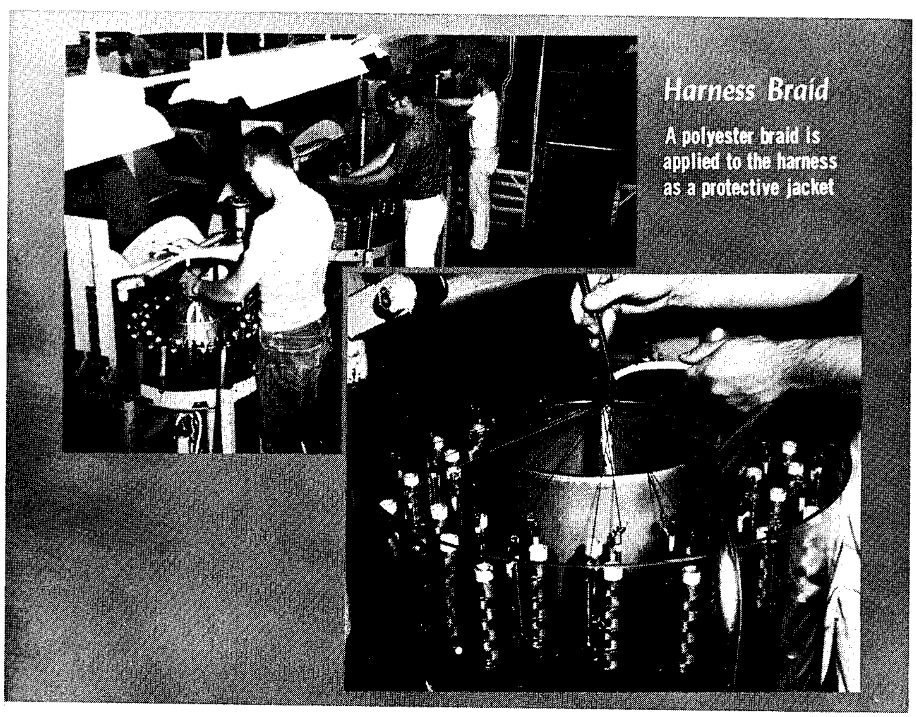

Harness Braid
A polyester braid is
applied to the harness
as a protective jacket

FIG. 8

THE DESIGN OF CABLE CONNECTOR COMBINATIONS TO ACHIEVE ELECTROMAGNETIC INTERFERENCE CONTROL

D. E. Clark
Electrical Components Division
The Bendix Corporation
Sidney, New York 13838

Summary

A presentation on the proper materials choice, fabrication techniques and methods of testing to assure the design of cable connector combinations for electromagnetic shielding effectiveness. Included are the test results of various cable braid and flexible conduit materials as evaluated using a Triaxial type test fixture.

Introduction

The goal of a properly designed cable-connector combination for Electromagnetic Interference (EMI) Control is two fold, as follows:

1. To prevent unwanted EMI from entering a system and appearing upon the cable's center conductors.

2. To prevent unwanted EMI from a system's center conductors from entering an outside environment.

   The former is known as susceptibility control and the latter is known as radiation control.

The Shielded System

The shielded system of a cable-connector combination to achieve EMI control consists of the following: (Ref. - Figure I)

1. The connector shell

2. The E. M. R. hardware: method of forming wires or attaching connector to cable braid or conduits.

3. The cable braid or conduit.

Points of Probable EMI Leakage from the Shielded System

EMI leakage can occur in the shielded system from one of two or a combination of the following causes: (Ref. Figure 1)

1. Leakage from points 1 and 4:
   In the case of points 1 the connector mating surfaces may make improper shell contact with its mating counter-part. At points 4 improper soldering or brazing of the braid or conduit to the E. M. R. hardware may cause EMI leakage in these areas.

2. Penetration of the system at points 2, 3 and 5: Penetration of the system can occur at the above points either through the improper selection of material thickness or the selection of materials whose electrical properties are inadequate for the desired frequency range to be shielded.

Types of EMI Leakage Fields

Electromagnetic fields are normally classified into one of the following basic types:

1. High impedance E fields- are fields that exist in the vicinity of high impedance radiators which develop large voltage potentials at low current levels and exhibit intrinsic impedances greater than 377 ohms.

2. Low impedance H fields- are generated by radiators which exhibits large current flow with little impressed voltages. Their intrinsic impedance is less than 377 ohms, usually less than 1 ohm. They normally exist at frequencies below 100 KHz.

3. Plane wave fields- exist in free space far removed from the radiator and have an intrinsic impedance equal to 377 ohms. Both E and H fields become plane wave fields at distances greater than one wave length from the radiator.

Shielding Effectiveness Design

The degree of cable-connector EMI control can be calculated in decibels of shielding effectiveness (S. E.)[2]

where S. E. = A + R + B

A is the absorption loss in decibels equal to $3.34 \times 10^{-3} T \sqrt{FUG}$ (1)

- T = Thickness in mils
- F = Frequency in Hertz
- U = Relative Permeability of the Shield Material, Relative to Copper
- G = Relative Conductivity of the Shielded Material, Relative to Copper

The table below lists common handbook values of relative permeability and conductivity for various common shield materials and platings used in cable-connector combinations.[2]

TABLE I

Metal	G	U
Copper (Annealed)	1.0	1.0
Silver	1.05	1.0
Gold	0.70	1.0
Aluminum	0.61	1.0
Brass	0.26	1.0
Cadmium	0.23	1.0
Nickel	0.20	1.0
Steel AMS 5045	0.10	1000
Monel	0.04	1
400 Series Stainless Steel	0.02	1000
48% Nickel-Iron	0.0385	5000

The R term is the reflection loss value for a particular metal and varies according to the type of leakage field peresent at the shield,

For E Fields $RE = \left[353.6 + 10 \log_{10} \frac{G}{F^3 U^2}\right] db$ (2)

For H Fields $RM = \left[20 \log_{10} \frac{.462}{r \sqrt{\frac{FG}{U}}} + .136\, r \sqrt{\frac{FG}{U}} + .354\right] db$ (3)

For Plane Wave Fields $R = \left[108.2 + 10 \log_{10} \frac{G \times 10^6}{UF}\right] db$ (4)

In all cases where r is a factor it is equal to the distance from the source to the shield in inches.

The B term is a re-reflection quantity and is very complex in nature. If the design is such that A is greater than 15 decibels at the minimum frequency to be shielded it can be ignored. For example, for 48% nickel iron A is greater than 15 decibels above 12 KHz for 3 mil material, 4.23 KHz for 5 mil material and 1 KHz for 10 mil material. These thicknesses are typical of material used for convoluted flexible leads.

A second method of calculating H field shielding effectiveness exists. This method is defined on page 131 of Terman's first edition of the "Radio Engineers' Handbook". The method states that for cylinders whose length is a number of times its diameter the shielding effectiveness to uniform magnetic fields results from "skin effect" losses.

$$SE_H = 20 \log_{10} 0.35 \ \underline{r} \ e^{\frac{T}{\delta}} \times 10^{-3} \quad (5)$$

where $\frac{T}{\delta}$ must be greater than 2

r is the radius of the cylinder in inches

T is the thickness of the cylinder in mils

δ equals the skin dept in inches $= \frac{2.61}{\sqrt{FUG}}$

Where F, U and G are the same units used above.

Figure 2 shows the calculated shielding effectiveness of E and H field radiation versus various thicknesses of 48% nickel-iron conduit. The three and five mil thicknesses are standard with various vendors. The ten mil thickness can be obtained on special order.

The curve shows for typical requirement of shielding effectiveness of 100 decibels, the E fielding shielding requirements could theoretically be met. H field requirements in all probability would not be met in the lower frequency range of 15 KHz to 600 KHz, depending upon the thickness chosen. Equations 1, 2 and 3 were used to establish Figure 2.

Figure 3 is a comparison of two methods of calculating H field shielding effectiveness. Curve I and II show the calculated difference between the method using equation 1 and 3 and the skin effect method of equation 5.

Curve III of Figure 3 shows the additional H field shielding effectiveness that can be achieved by twisting current carrying center conductors within the shield. The reduction of H field by twisting current carrying wires was measured in the laboratory using the following procedures:

The H field for an infinitely long wire was established using Biot-Savert's relationship;

$$H = \frac{0.2I}{r}; \qquad (6)$$

where H is the field in oersteds, I the current in amperes, and r the distance from the wire in centimeters. A current of 1 ampere was established in the wire and the field was measured from 15 KHz to 100 MHz using the measurement method RE01 of MIL-STD-461A and 462.

When the return wire was laid parallel to the incident wire, a reduction of 30 decibels was noted for the 1 ampere generated field from 15 KHz to 100 KHz.

When the return wire was twisted to the incident wire another 30 decibel reduction from 15 KHz to 100 KHz was noted. This resulted in a total reduction of 60 decibels for a twisted wire versus an infinitely long wire.

In a practicable construction the infinite long single wire will not exist, but parallel wires may be present. Curve III was established to show the maximum theoretical H field shielding effectiveness available from 5 mil nickel-iron, by adding the 30 decibel gain achieved by twisting the wires, to the skin effect value calculated in Curve I.

Doubt exists as to the validity of the handbook values for the permeability of various materials shown in Table I. Several reasons for this doubt exists, and are as follows:

1. Figure 4 is handbook published data showing the change in permeability for iron with respect to increasing frequency. We have been unable to find published data on other ferrous materials listed in Table I but it is suspected that the higher permeability materials will exhibit like changes of permeability at even lower frequencies than the iron.[2]

2. Some data was available that did show magnetic stainless steel, when formed into connector shells gave a maximum permeability of 400 instead of 1000 as shown in Table I. This maximum value of 400 only occurred when the connector shell was measured at a flux density of 15 kilogausses. For low gauss levels the measured permeability was less than 400. Of course, where the material was saturated above 15 kilogausses, the permeability was much less than 400. These measurements were performed at a test frequency of 60 Hz.

3. It seems probable that the permeability of a given material could be altered drastically by machining, brazing and forming operations necessary in the manufacture of cable-connector configurations. Therefore, calculated values of H field shielding effectiveness may prove higher than actual measured values.

4. Some preliminary H field leakage measurements made on solid drawn tubes of various ferrous materials did show shielding effectiveness results that were much lower than theory predicted for these materials. One explanation for these results was that the UG product for the materials, in actuality, was much lower than the stated handbook values.

Test Method - E Field Shielding Effectiveness Testing

This Division expended a large effort evaluating many test methods for measuring the shielding effectiveness of cable-connector combinations. After much evaluation it was decided to use the Triaxial method of test developed at General Radio by John Zorzy and R. Muehlberger. This test method offers several advantages as follows:

1. The principle of operation is such that the test results are not a function of the test chamber size and shape.

2. Data can be repeated with greater accuracy.

3. All of the power sources and detectors are commercially available items and can be calibrated to standards traceable to the National Bureau of Standards.

Test Method Prerequisites:

The necessary prerequisites of such a test method are as follows:

1. The EMI incident power into the test sample must be obtained throughout the frequency spectrum. This will entail a matched system including the test sample and its termination.

2. The EMI incident power which will leak from the test sample must be collected throughout the frequency spectrum. This power must manifest itself in its true form across a known output impedance.

The Triaxial Test Method

The Triaxial test method is basically a controlled double coaxial test environment. Figure 5 shows a schematic of such a system including a signal source and a detector. The test sample and signal source comprise the inner coax. The outer coax consists of a carefully designed silver plated brass tube whose dimensions with respect to the inner coax will produce the necessary characteristic impedance compatible with the detector.

Impedance Z_{2G} consists of an adjustable piston type shorting ring when the device is used for testing in the 100 MHz to 10 GHz frequency range. Adjusting this short for a maximum detector reading across Z_{2L} give the matched power indication of the test sample leakage. Z_{2G} may be replaced with a coaxial 50 ohm resistor when testing in the 10 KHz to 100 MHz frequency region. This makes necessary a 6 decibel leakage power correction factor which must be added to the detector power measurement in order to obtain the true leakage power in this frequency spectrum.

Test Sample Design - Inner Coax System

Figure 6 is a diagram showing a representative test sample. When testing connector joint leakage the shield braid shown on the diagram consists of a solid tube, .030" wall thickness, whose material is silver plated low carbon steel. The diameter of this tube, in conjunction with the dielectric and the center conductor diameter is determined by the impedance of the signal generator or power source. In most cases this test sample must be designed to present as nearly as possible a characteristic impedance of 50 ohms. The center conductor through the test connector is also designed to present a 50 ohm impedance. One end of the test sample is terminated in the signal source and the opposite end must be determined in a resistor (Z_L) equal to the sample characteristic impedance and the source impedance (50 ohms). The terminating resistor must maintain its resistance into the gigahertz test frequency region. Small mismatches can be tolerated by measuring the incident and reflected power into the sample and calculating the true power. The above design allows the test engineer to accurately measure the true power into the test sample. A similar arrangement can be made to test braid and conduit test samples.

The Outer Coaxial System

The design of this system depends upon the diameter and length of the test sample. If the maximum outside diameter of the test sample is assumed as the center conductor of the outer coaxial system and the detector input impedance is maintained at 50 ohms, then standard coaxial air dielectric calculations will determine the inner diameter of the outer shield. The shorting adjustable piston will insure matched conditions at the detector throughout the 100 MHz to 10 GHz frequency range. The length of the outer coaxial tube with respect to the test sample length determines the lowest usable frequency when using the shorting piston.

Mode Propagation Control

The test sample must be centered within the outer coaxial shielding for proper mode propagation of the leakage fields toward the detector. The test sample field components could be either radial, axial, or circumferential in direction. These leakage components are not necessarily symmetric in nature and locally TE, TM, and TEM modes could exist. The test fixture should couple all of the modes to the detector. At present no one standard method of tests can combine all of these possible modes into accurate meaningful data.

The triaxial method with its coaxial arrangement makes possible only the propagation of the TEM mode below 1 gigahertz. The TEM mode is the mode most likely to cause interference difficulties to equipment adjacent to a cable-connector combination.

Between 1 and 10 gigahertz a TE_{11} mode could exist but not be propagated to the detector. The concentric mounting of the test sample and the proper design of outer braid transition adapters can minimize this error, to a great degree, by preventing the initial generation of the TE_{11} mode, thereby increasing the fixture's usefullness in measuring the TEM mode in this frequency range.

Test Equipment

Figures 7, 8, 9, 10 and 11 are block diagrams and photographs showing test equipments and their arrangements to perform input power and leakage power measurements. These figures span a frequency range of from 15 KHz to 10 GHz.

The test equipment is available as shown or it's equivalent is available at most manufacturers or test agencies who do extensive EMI control programs.

Test Data

The input power leakage must be put into a form whereby they can be related to environmental impedances other than the 50 ohm. The leakage areas in a particular test sample size must be given a designation whereby the system designer can use this designation for his particular environmental conditions. This designation can be likened to an impedance parameter called the surface transfer impedance (S. T. I.). The S. T. I. for a particular connector is $Z_{21} = \frac{e_2}{i_1}$ where e_2 equals the equivalent leakage voltage within the external coaxial line, and i_1 equals the current flowing in the test sample or the inner coaxial line.

In a 50 ohm system the incident power P_1 to $50\ i^2$.

The output leakage power, P_2 in a 50 ohm system is $\frac{e_2^2}{50}$.

The measured power ratio A is equal to P_2/P_1.

Therefore:

$$A = \frac{\frac{e_2^2}{50}}{50\ i_1^2} = \frac{e_2^2}{(50)^2\ i_1^2}$$

By substitution and definition the S. T. I. equals

$$Z_{21} = \frac{e_2}{i_1} = 50\sqrt{A} \text{ Ohms for connector interference leakage} \quad (7)$$

$$Z_{21} = \frac{50\sqrt{A}}{L} \text{ Ohms/Cm. where L equals the test sample length in Cm for cables and conduits.} \quad (8)$$

The characterstic Z_{21} or S. T. I. is independent of the external impedance loading so can be used to calculate EMI leakage, knowing certain environmental conditions such as: Susceptibility levels of nearby equipments, the impedance of the surrounding media and the EMI power available within the test sample.

Test Results - E Field

Connectors

Figure 12 shows typical shielding effectiveness data for both LJT and JTG connectors. These connectors both have ground fingers internal to their plug shells.

For the JT connector series without ground fingers, tests at E. C. D. and at Picatinney Arsenal show a 20 decibel degradation in shielding effectiveness from that shown on Figure 12.

Figure 12 also shows that both the LJT and JTG type connectors would meet the requirements of Table VIII of MIL-C-81511B with respect to minimum leakage limit.

Connector Backshell Terminations

Figure 13 shows the advantage gained in using the 10-352424 solder type EMR hardware to fasten a shield braid to a connector backshell. This method of termination is compared to a commonly used pigtail type termination fastened under the connector's strain relief clamp, such as the type JT-RE(SR) connector.

Shielded Braids and Conduits

Figure 14 is a family of shielding effectiveness curves for various seamless 6 mil thick solid tubes. Above 10 MHz the shielding effectiveness of the 52 alloy (nickel-iron) and 1010 steel appears to flatten out and then decrease above 200 megahertz. This is undoubtedly due to a decrease in UG products, with the permeability decrease causing a decrease in this product.

Above 10 MHz all materials surpassed the shielding effectiveness of a single layer tinned copper braid.

Figure 15 is a series of comparative shielding effectiveness performance curves on various annular and helical conduit materials. Their performance is compared with that of a single layer copper braid shield. The American Metal Hose type AT2198-300 conduit, Curve VI was superior to all others tested. The non-magnetic stainless steel curve V gave the least desirable performance.

The curves on Figure 16 represent a comparison in shielding effectiveness performance between various braids and conduits. Of interest is a comparison of Curves III and IV.

These two curves show that a 10 to 20 decibel improvement can be obtained using double copper braid versus a single copper braid. A single layer magnetic steel braid as shown on Curve IV gives the poorest performance of all the samples tested. The braids also show a decrease in shielding effectiveness above 1 MHz while the conduits do not.

Cable-Connector Combinations

Figure 17 shows that when the four types of connectors tested are terminated to a double copper braid shield the type of connector makes very little difference as to shielding effectiveness performance. The dashed curve shows that the braid shield in this case is the limiting factor in shielding effectiveness performance. All braid terminations to the connector backshells were made using 10-353424 type EMR hardware.

Figure 18 consists of curves showing the performance of the LJT connector, using various shield materials to make a cable-connector combination. Once again this shows that the connector performance is limited by the shield material used on the braid.

Conclusions and Recommendations

Several conclusions and recommendations regarding the design of cable-connector combinations to achieve maximum Electromagnetic Interference control are apparent from the data in this report and also from a study of some of the referenced articles. These conclusions and recommendations are as follows:

1. The connectors tested in this report will not be the limiting factor in EMI control when either single or double copper cable braids are used.

2. The connectors using the 360° peripheral beryllium copper alloy spring fingers on their plug shells, give a consistent 20 decibel improvement in shielding effectiveness over their non spring counter parts.

3. Most flexible conduits will give consistently superior performance in shielding effectiveness when compared to braid shields.

4. EMR hardware used to attach braids and conduits to connector backshells be of the solid solder on type construction similar to our 10-353434 series. This has proven to be far superior to pigtail type of termination. Crimp terminations if properly performed with a 360° crimp have proven successful, but their performance will sometimes degrade when exposed to various environmental changes so they may be less reliable. Jacketing the cable with insulated molding compounds would prevent or retard this degradation.

5. Twisting current-carrying wire pairs will reduce the needed EMI shielding by as much as 30 decibels when compared to parallel current-carrying wires.

6. The cable-connector combination should be as short as possible, consistent with system performance to prevent cable length resonances from occurring within the prescribed system EMI frequency range. This is to prevent the cable from becoming an efficient receiving or transmitting antenna.

   Above the operating frequency range of 100 KHz multiple grounding of the cable shield will prevent this resonant condition from occurring. The grounds should be spaced no longer than 0. 15 of the wavelength distance in meters for the highest frequency to be excluded.

   Below the operating frequency range of 100 KHz multiple grounding of the system, including the cable, should not be done. Here, a single point system ground is usually necessary to prevent the circulation of low frequency currents between the multiple ground points. This ground, in most instances should be at the signal source end of the cable.

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6. MIL-C-81511B (Navy) 1 May 1968 Connectors, Electric, Circular, High Density, Quick Disconnect, Environment Resisting General Specifications For

7. MIL-STD-461A 1 August 1968 Electromagnetic Interference Characteristics Requirements for Equipment

8. MIL-STD-462, 31 July 1967 Electromagnetic Interference Characteristics Measurements of

9 MIL-STD-463, 9 June 1966. Definitions and Systems of Units, Electromagnetic Interference Technology

10. R. F. Leakage Characteristics of Popular Coaxial Cables and Connectors, 500 Mc to 7.5 G. C. by John Zorzy and R. F. Mulberger
Microwave Journal, November 1961

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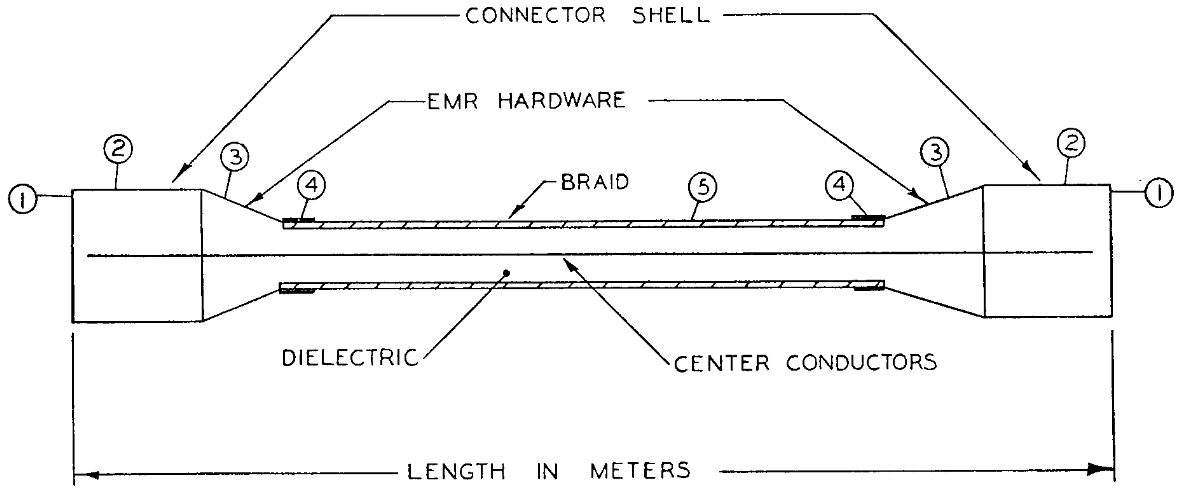
BIOGRAPHY

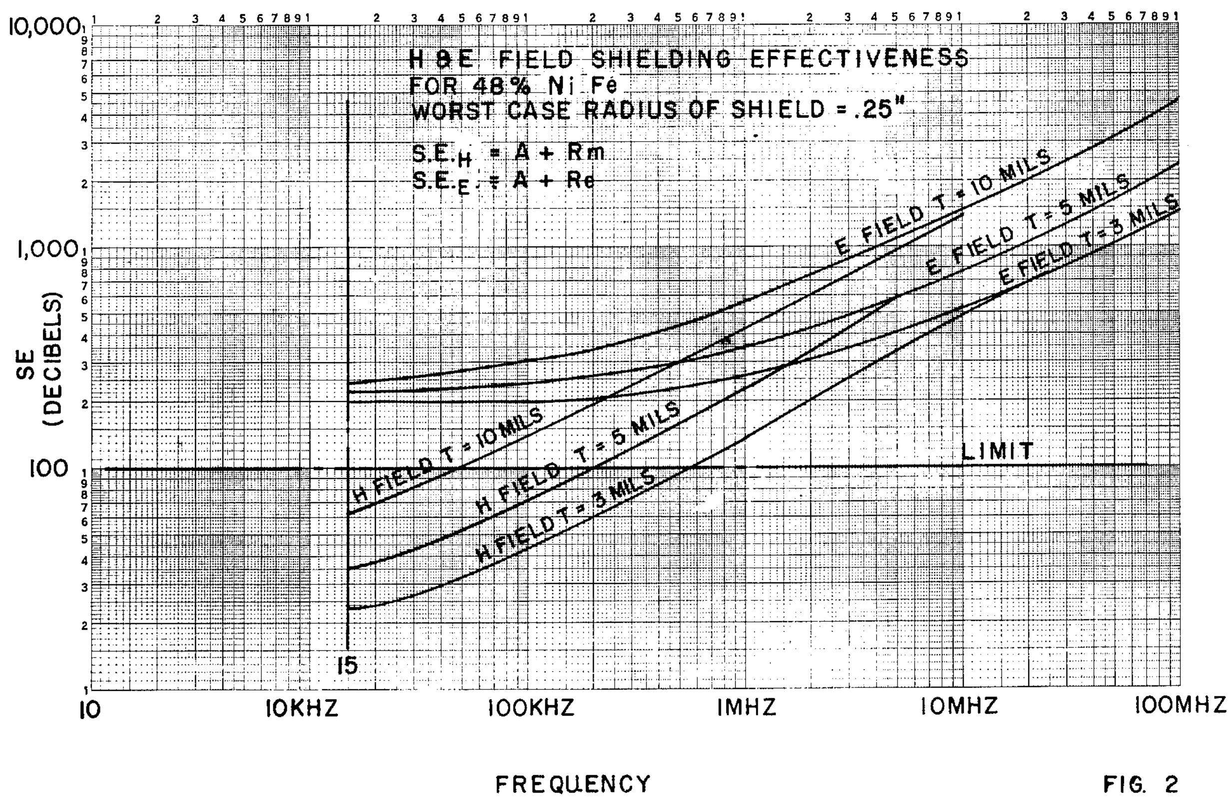
Mr. Clark was born in Johnson City, New York in 1926 and presently resides at RD #1 Nineveh, New York with his wife and two children. He is a veteran of both World War II and the Korean conflict and is a 1951 graduate of Norwich University with a BSEE.

During his twenty years of employment with the Bendix Corporation, fifteen years have been spent in the field of Electromagnetic Interference Control. The activity in this field encompasses work performed as an industry representative on SAE Committee AE-4 on Electromagnetic Compatibility during which time he aided in the preparation of industry comments on most existing military interference specifications and standards.



CONNECTOR SHELL
EMR HARDWARE
BRAID
DIELECTRIC
CENTER CONDUCTORS
LENGTH IN METERS

FIG. 1



H & E FIELD SHIELDING EFFECTIVENESS
FOR 48% Ni Fe
WORST CASE RADIUS OF SHIELD = .25"
S.E.H = A + Rm
S.E.E = A + Re
E FIELD T = 10 MILS
E FIELD T = 5 MILS
E FIELD T = 3 MILS
H FIELD T = 10 MILS
H FIELD T = 5 MILS
H FIELD T = 3 MILS
LIMIT
15
10,000
1,000
100
SE (DECIBELS)
10
10KHZ
100KHZ
1MHZ
10MHZ
100MHZ
FREQUENCY

FIG. 2

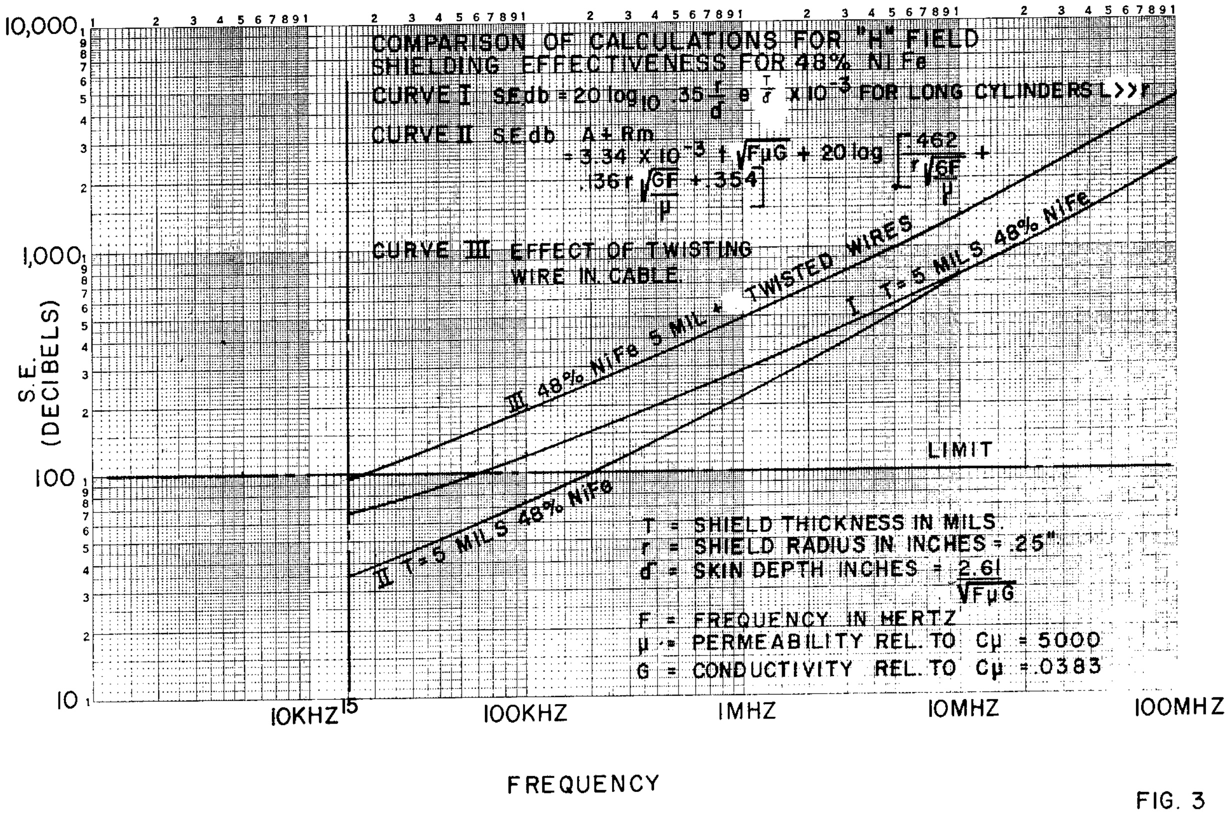

COMPARISON OF CALCULATIONS FOR "H" FIELD SHIELDING EFFECTIVENESS FOR 48% Ni Fe
CURVE I SEdb = 20 log10 .35 r/d e T/d x 10^-3 FOR LONG CYLINDERS L>>r
CURVE II SEdb A + Rm = 3.34 x 10^-3 t √FμG + 20 log [462/r√(GF/μ) + .36r √(GF/μ) + 354]
CURVE III EFFECT OF TWISTING WIRE IN CABLE
III 48% NiFe 5 MIL + TWISTED WIRES
I T = 5 MILS 48% NiFe
II T = 5 MILS 48% NiFe
LIMIT
T = SHIELD THICKNESS IN MILS.
r = SHIELD RADIUS IN INCHES = .25"
δ = SKIN DEPTH INCHES = 2.61/√FμG
F = FREQUENCY IN HERTZ
μ = PERMEABILITY REL. TO Cμ = 5000
G = CONDUCTIVITY REL. TO Cμ = .0383
10,000
1,000
100
10
S.E. (DECIBELS)
10KHZ
15
100KHZ
1MHZ
10MHZ
100MHZ
FREQUENCY

FIG. 3

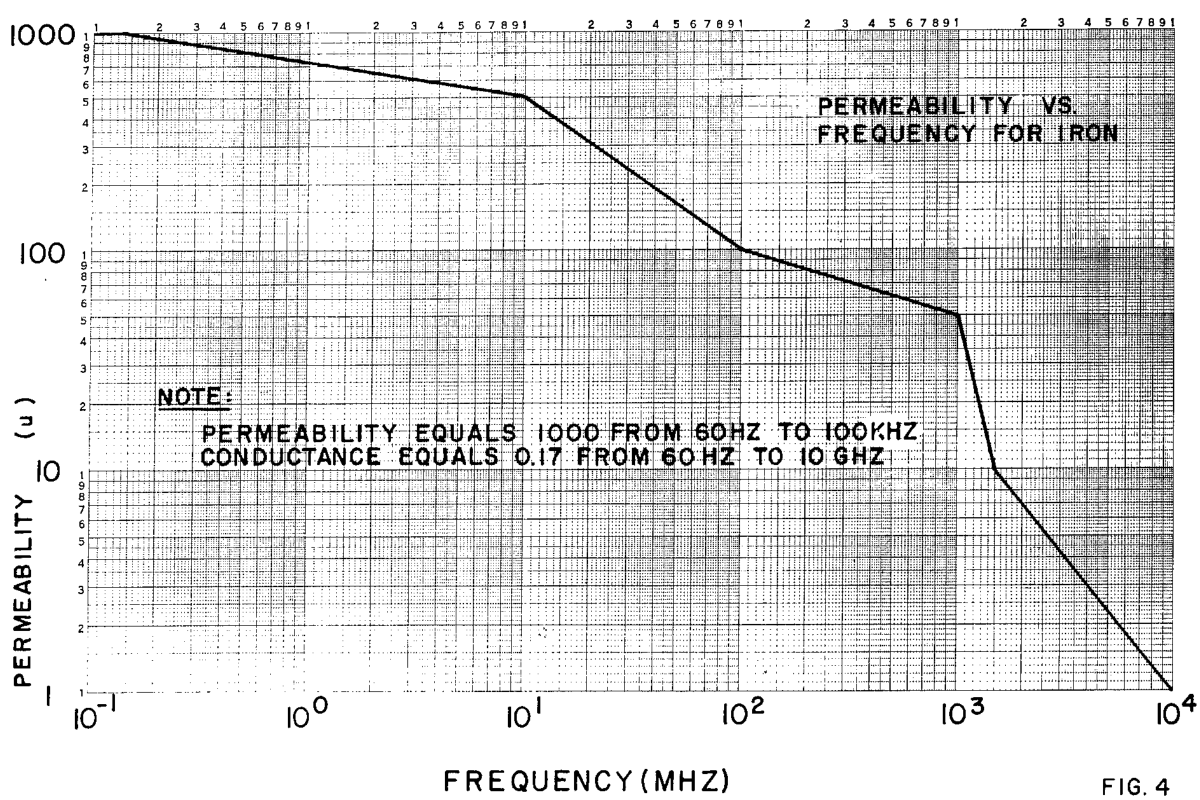

PERMEABILITY VS. FREQUENCY FOR IRON
NOTE:
PERMEABILITY EQUALS 1000 FROM 60HZ TO 100KHZ
CONDUCTANCE EQUALS 0.17 FROM 60 HZ TO 10 GHZ
1000
100
10
1
PERMEABILITY (u)
10^-1
10^0
10^1
10^2
10^3
10^4
FREQUENCY (MHZ)

FIG. 4

SCHEMATIC OF TRIAXIAL TEST UNIT
AND EQUIPMENT RELATIONSHIPS

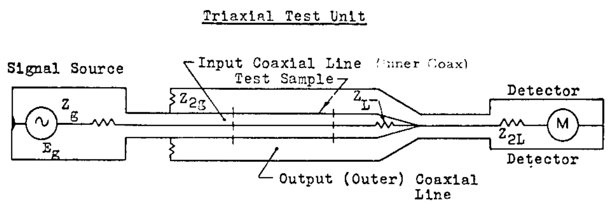


FIG. 5

TEST SETUP (15 KHz TO 200 KHz)

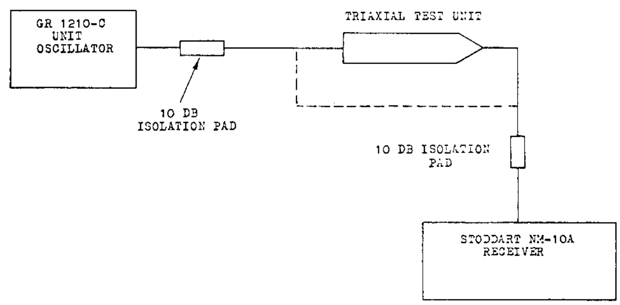


FIG. 7

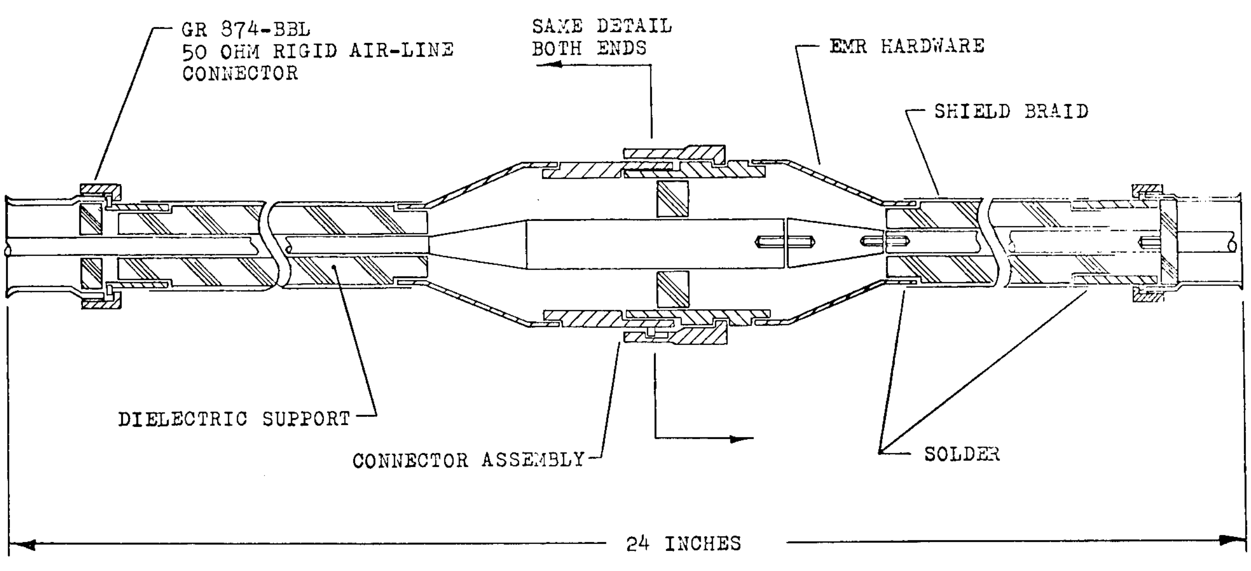


FIG. 6

TEST SETUP (200 KH_z TO 1000 MH_z)

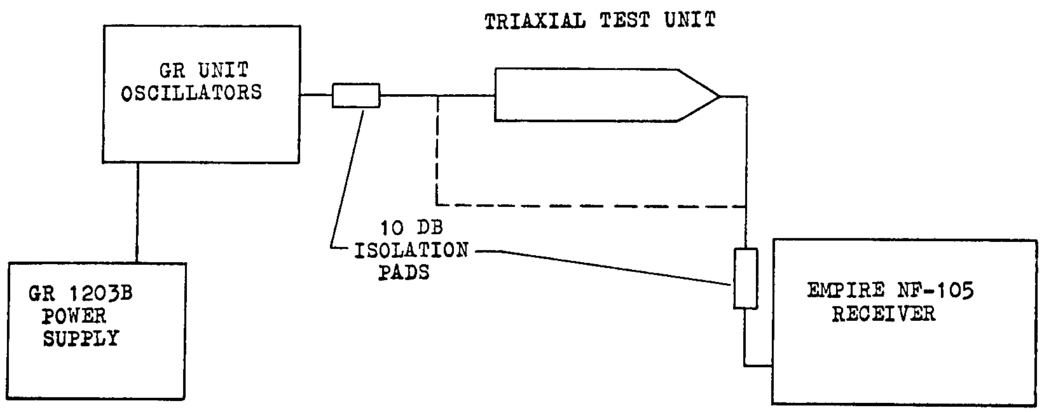


FIG. 8

TEST SETUP (1 GH_z TO 10 GH_z)

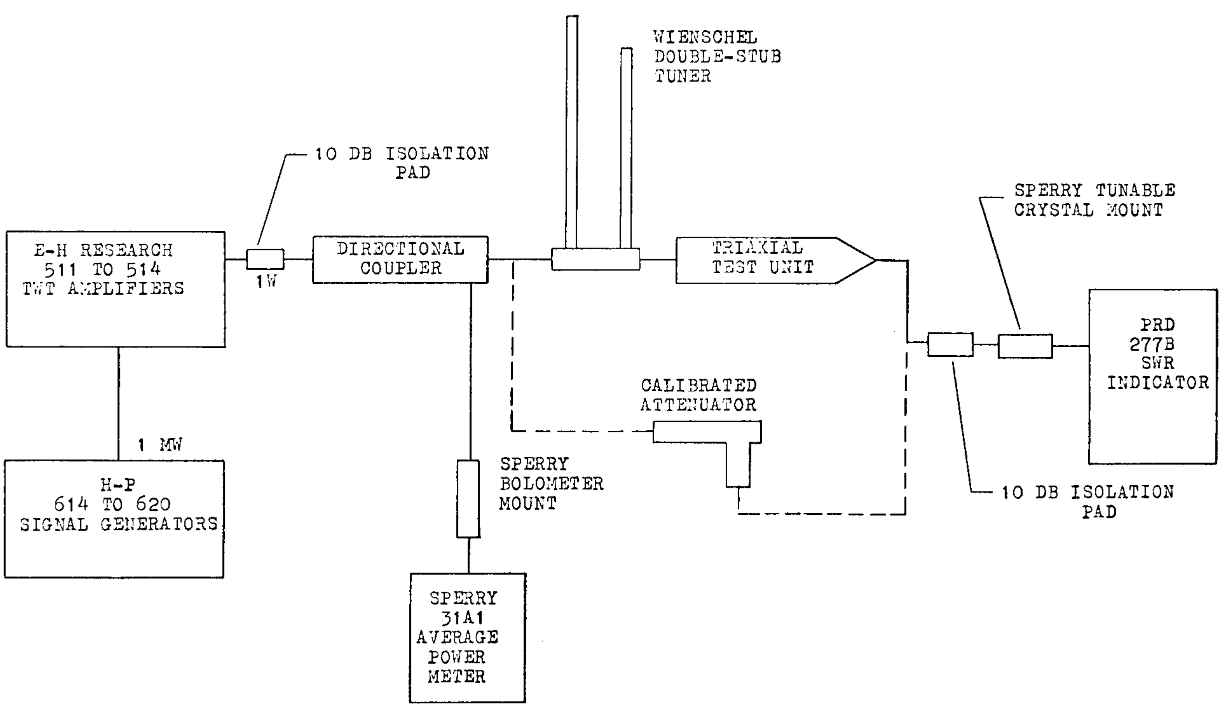
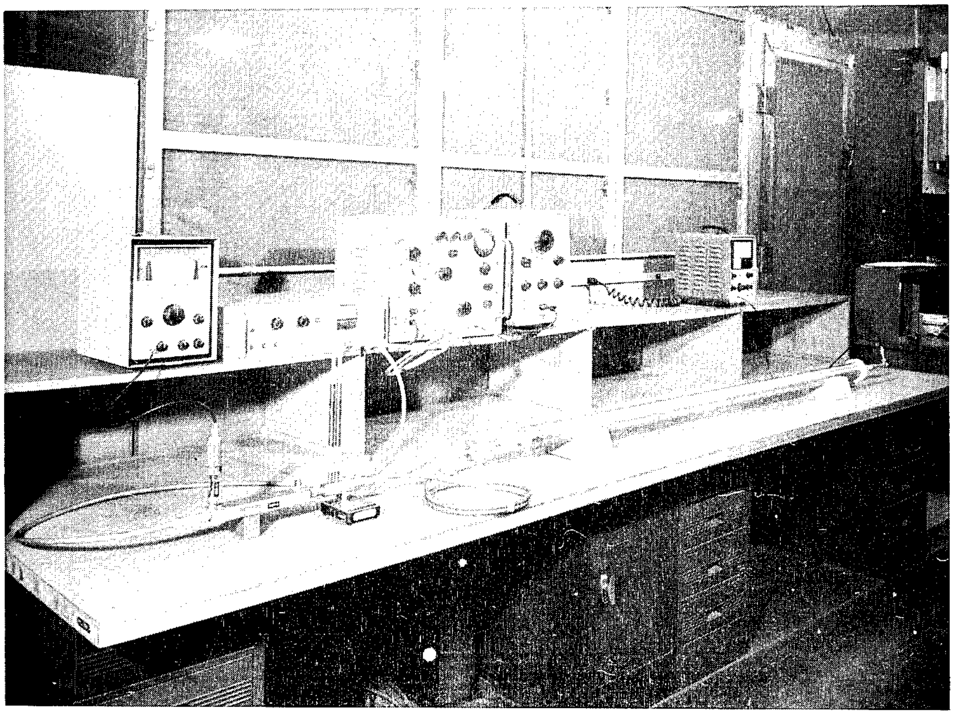
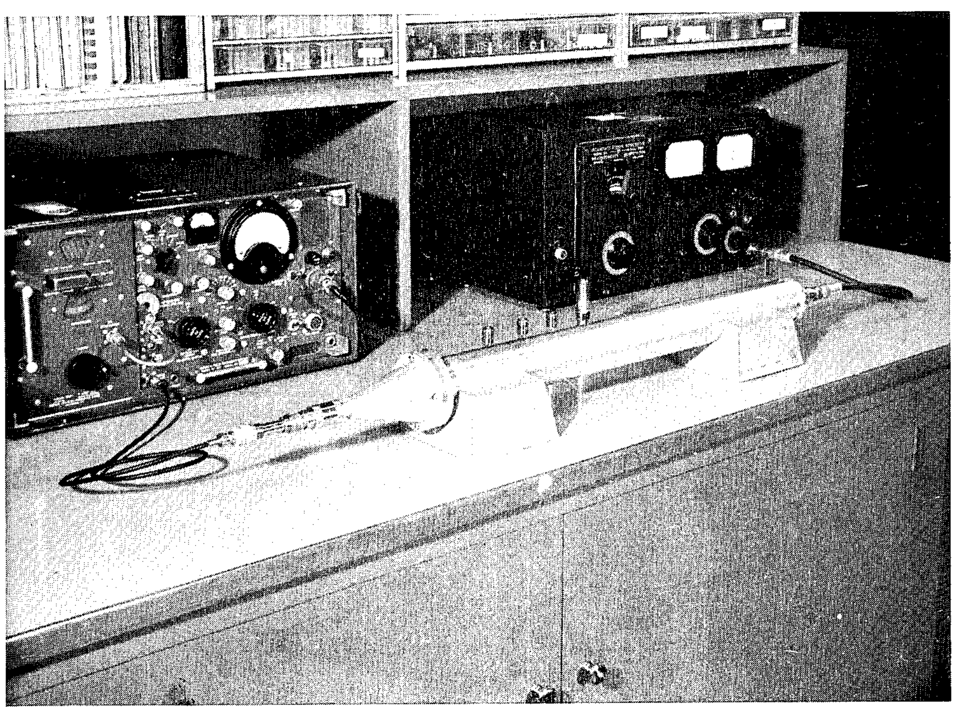


FIG. 9



TYPICAL TEST SET UP (1 TO 10 GHZ) FIG. 10



TYPICAL TEST SET UP (BELOW 1 GHZ) FIG. 11

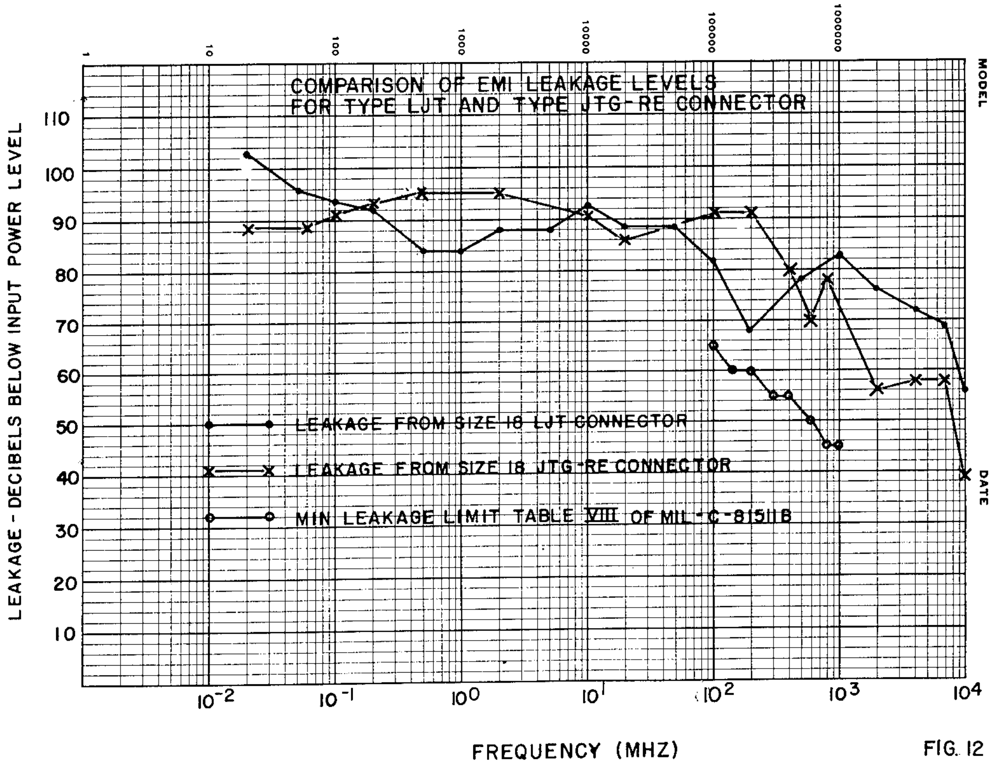

COMPARISON OF EMI LEAKAGE LEVELS
FOR TYPE LJT AND TYPE JTG-RE CONNECTOR
LEAKAGE - DECIBELS BELOW INPUT POWER LEVEL
LEAKAGE FROM SIZE 18 LJT CONNECTOR
LEAKAGE FROM SIZE 18 JTG-RE CONNECTOR
MIN LEAKAGE LIMIT TABLE VIII OF MIL-C-81511B
FREQUENCY (MHZ)

FIG. 12

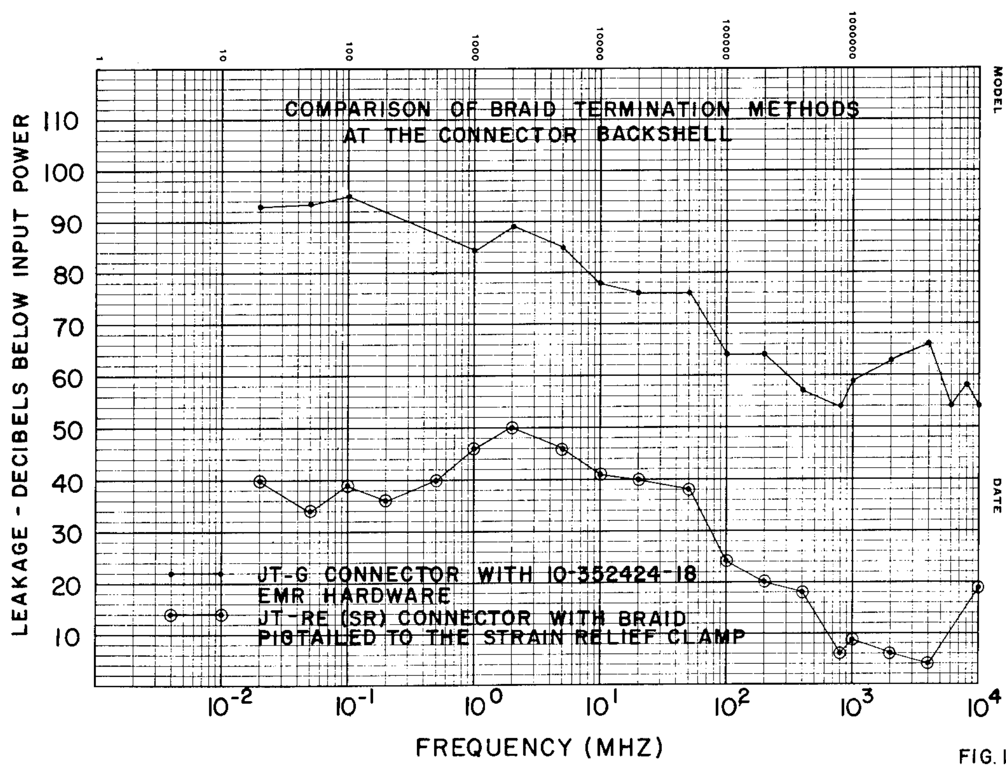

COMPARISON OF BRAID TERMINATION METHODS
AT THE CONNECTOR BACKSHELL
LEAKAGE - DECIBELS BELOW INPUT POWER
JT-G CONNECTOR WITH 10-352424-18
EMR HARDWARE
JT-RE (SR) CONNECTOR WITH BRAID
PIGTAILED TO THE STRAIN RELIEF CLAMP
FREQUENCY (MHZ)

FIG. 13

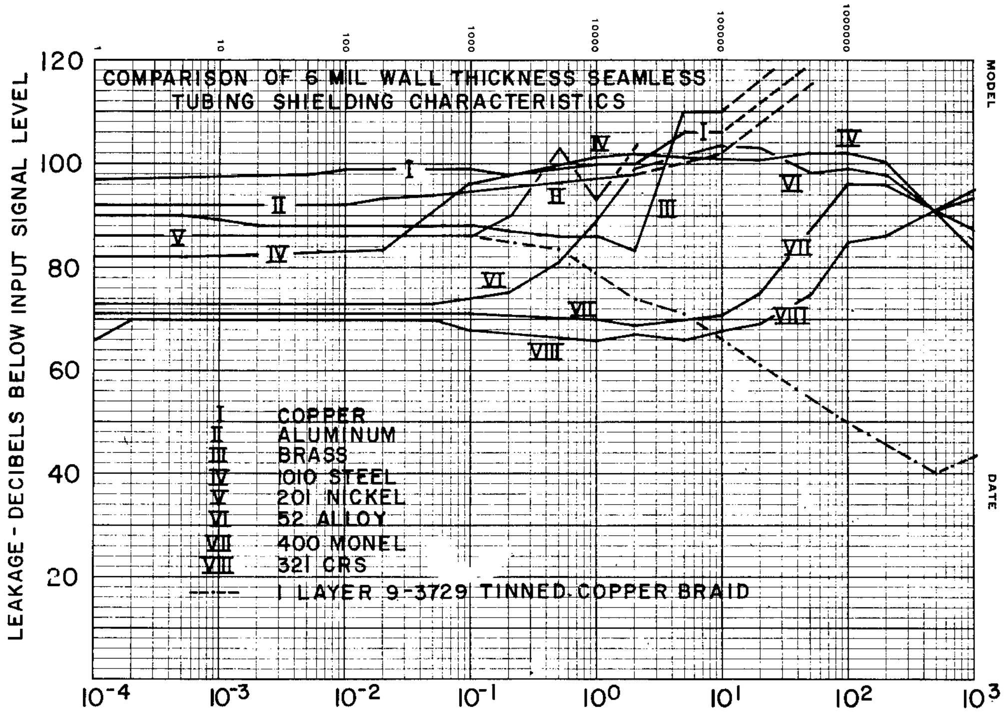

COMPARISON OF 6 MIL WALL THICKNESS SEAMLESS TUBING SHIELDING CHARACTERISTICS
LEAKAGE - DECIBELS BELOW INPUT SIGNAL LEVEL
FREQUENCY (MHZ)
I COPPER
II ALUMINUM
III BRASS
IV 1010 STEEL
V 201 NICKEL
VI 52 ALLOY
VII 400 MONEL
VIII 321 CRS
I LAYER 9-3729 TINNED COPPER BRAID
MODEL
DATE

FIG. 14

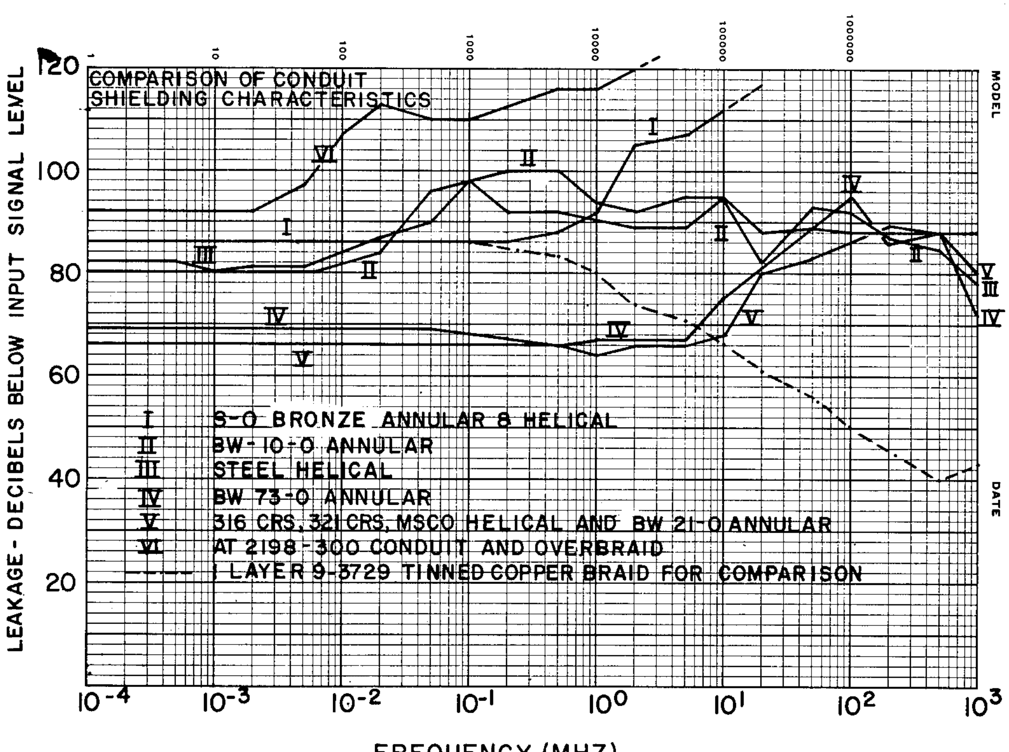
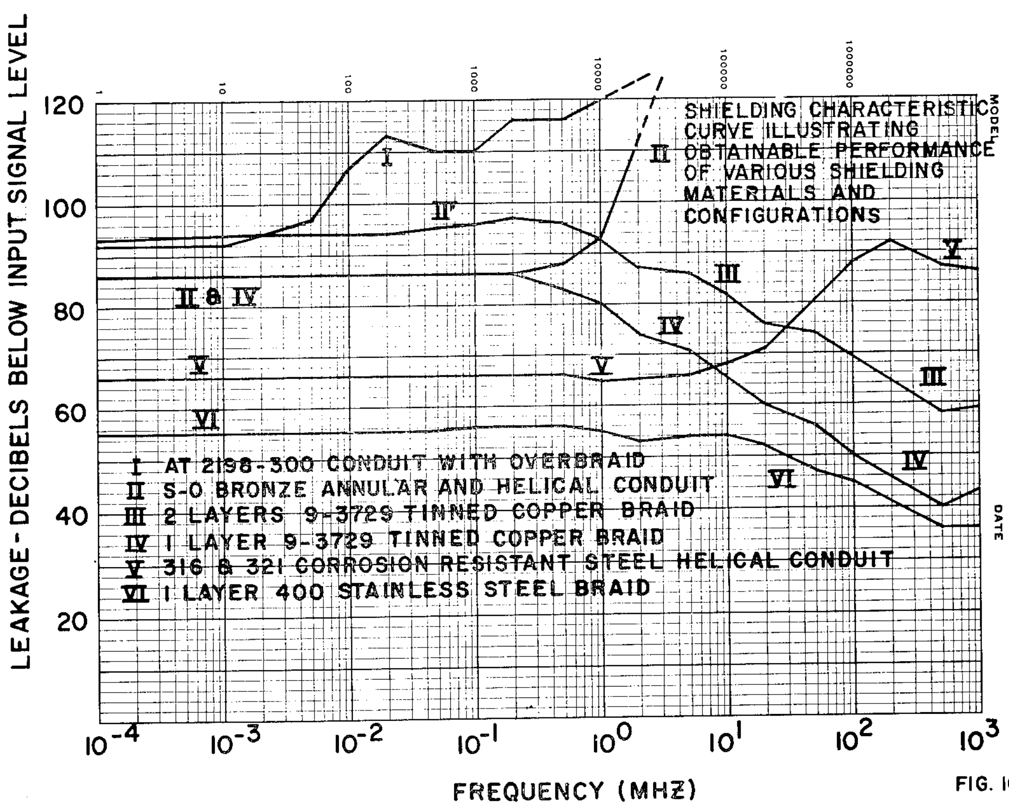
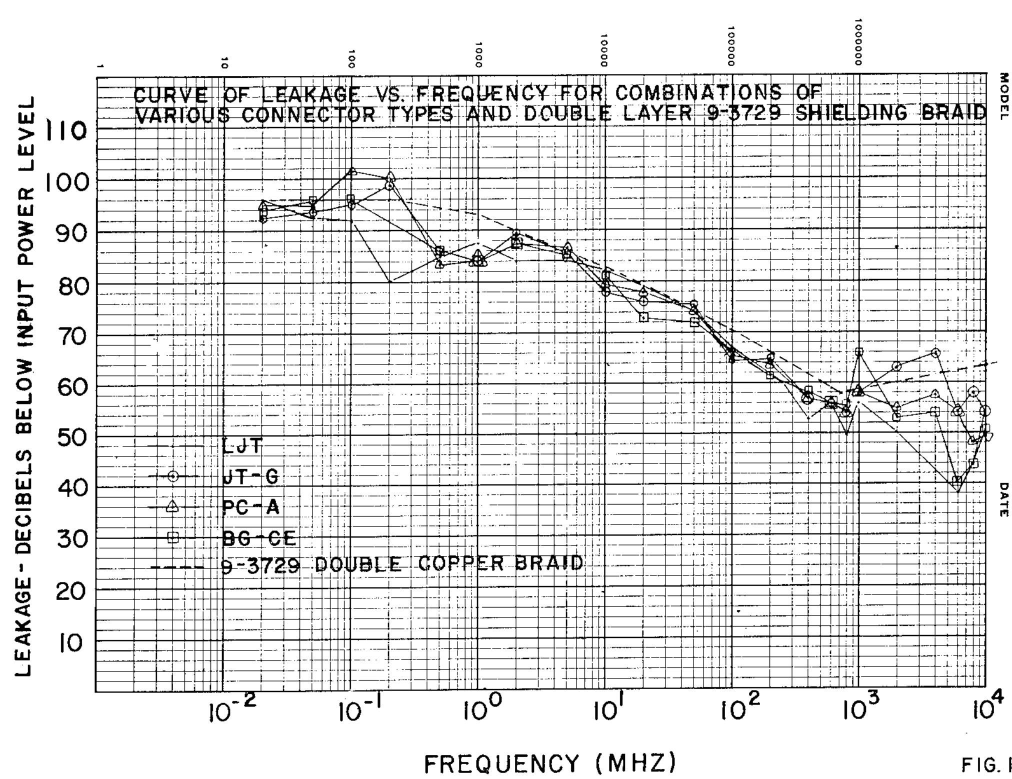

COMPARISON OF CONDUIT SHIELDING CHARACTERISTICS
LEAKAGE - DECIBELS BELOW INPUT SIGNAL LEVEL
FREQUENCY (MHZ)
I S-O BRONZE ANNULAR & HELICAL
II BW-10-O ANNULAR
III STEEL HELICAL
IV BW 73-O ANNULAR
V 316 CRS, 321 CRS, MSCO HELICAL AND BW 21-O ANNULAR
VI AT 2198-300 CONDUIT AND OVERBRAID
I LAYER 9-3729 TINNED COPPER BRAID FOR COMPARISON
MODEL
DATE

FIG. 15



SHIELDING CHARACTERISTIC CURVE ILLUSTRATING OBTAINABLE PERFORMANCE OF VARIOUS SHIELDING MATERIALS AND CONFIGURATIONS
I AT 2138-300 CONDUIT WITH OVERBRAID
II S-O BRONZE ANNULAR AND HELICAL CONDUIT
III 2 LAYERS 9-3729 TINNED COPPER BRAID
IV I LAYER 9-3729 TINNED COPPER BRAID
V 316 & 321 CORROSION RESISTANT STEEL HELICAL CONDUIT
VI I LAYER 400 STAINLESS STEEL BRAID
LEAKAGE - DECIBELS BELOW INPUT SIGNAL LEVEL
FREQUENCY (MHZ)

FIG. 16



CURVE OF LEAKAGE VS. FREQUENCY FOR COMBINATIONS OF VARIOUS CONNECTOR TYPES AND DOUBLE LAYER 9-3729 SHIELDING BRAID
LJT
JT-G
PC-A
BG-CE
9-3729 DOUBLE COPPER BRAID
LEAKAGE - DECIBELS BELOW INPUT POWER LEVEL
FREQUENCY (MHZ)

FIG. 17

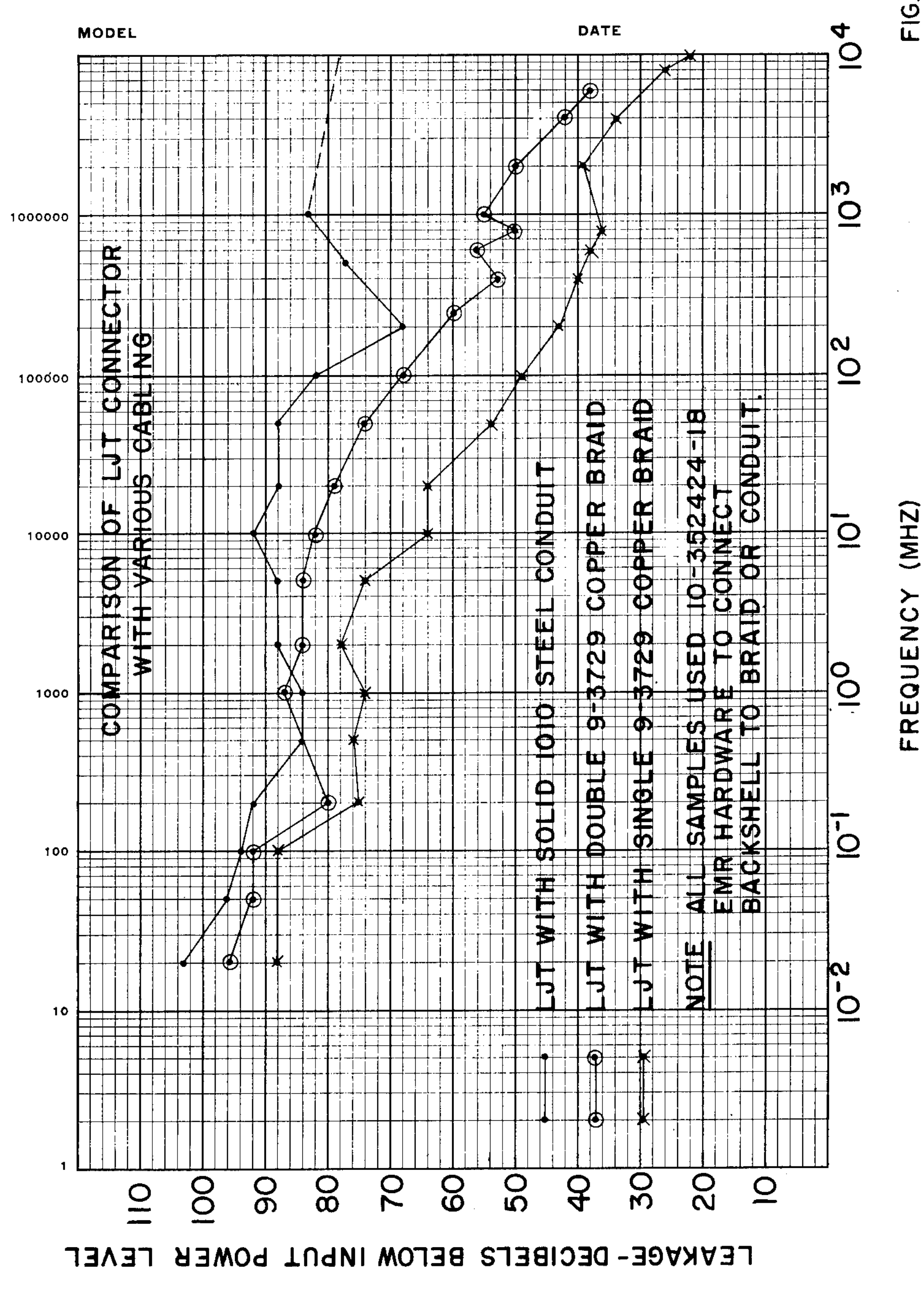

MODEL
DATE
COMPARISON OF LJT CONNECTOR
WITH VARIOUS CABLING
LJT WITH SOLID 1010 STEEL CONDUIT
LJT WITH DOUBLE 9-3729 COPPER BRAID
LJT WITH SINGLE 9-3729 COPPER BRAID
NOTE ALL SAMPLES USED 10-352424-18
EMR HARDWARE TO CONNECT
BACKSHELL TO BRAID OR CONDUIT.
FREQUENCY (MHZ)
LEAKAGE-DECIBELS BELOW INPUT POWER LEVEL
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
1
10
100
1000
10000
100000
1000000
110
100
90
80
70
60
50
40
30
20
10

FIG. 18

VACUUM-PRESSURE IMPREGNATION OF WATERPROOF CABLE & ASSOCIATED IN-LINE COMPOUND MIXING SYSTEM

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Baltimore, Maryland

A waterproof plastic insulated multipair cable for buried (Exchange Area Cable) telephone distribution routes is now being produced by Western Electric. The waterproof approach replaces the air in the core with a dielectric compound that permits the use of an economical sheath design and eliminates the need for gas pressuring.

All small pair size (25 pair and smaller) PIC Exchange Area Cable may be manufactured by forming the core in tandem with the sheathing operation. The core is formed by feeding twisted pairs into an oscillating face plate that imparts an alternating helical lay to the core to reduce cross talk and provide flexibility to the cable. The pairs are fed through specific individual apertures in the face plate to retain orientation and brought together by passing them through a sizing die. For waterproof cable, the oscillating face plate and the sizing die are mounted on opposite ends of a heated tank that contains liquid filling compound. As the pairs are drawn through the tank, they are coated by the liquid compound; and as the core is formed by a second sizing die in the tank, compound is entrapped, filling the interstitial space.

In order to fill cores larger than 25 pairs, attempts were made to do the filling at the stranding operation. Cores of 50 pairs and 100 pairs were filled by treating each unit of the core the same as the method previously described. The filled units were then formed into a cable core by the same procedure used for individual units. Cables can be made this way but the method is not desirable from a manufacturing standpoint. An increase in string-up time coupled with a reduction in stranding speed required to insure an adequate fill, reduces strander output by approximately one-half. In addition, the rotational speed of the strander take-up causes considerable accumulation of the compound in the take-up compartment. Since the normal time interval between stranding and sheathing in the shop allows the compound to cool while on a core truck, feeding the cooled core into a sheathing line causes small air pockets to be set-up in the filled core as it is unwound from the core truck. Finally, because the cable must be flooded with filling compound both under and over the aluminum shield, this approach requires handling the compound in two shop areas - stranding and sheathing.

It became evident that a method of filling prestranded cores in tandem with a sheathing line would be required to allow economical production of filled cables larger than 25 pairs.

The first approach to filling pre-stranded core was to apply room temperature compound at high pressure to the core in a vacuum. After an experimental model of the required apparatus was fabricated, studies of the compound characteristics by the Bell Telephone Laboratories showed that subjecting the filling compound to cold flow under pressure caused severe shearing of the polyethylene's molecular chains, destroying the flow characteristics needed at higher temperatures to which cables are subjected in the field. Therefore, this procedure was abandoned.

It was reasoned that a core, regardless of pair size or configuration, could be successfully filled at lower pressure if most of the air was removed prior to application of a liquid compound. This approach would allow use of rigid dies for the various chambers required without undue concern for things like compound leakage, normal variation in core diameter or the substantial decrease in core size at the joint for tying two cores together for continuous operation. Based on such a vacuum-low pressure liquid compound approach, equipment for it has been developed and demonstrated.

The apparatus can be considered as four separate compartments as shown in Figure 1:

1. Vacuum Section
2. Vacuum-Pressure Gradient Section
3. Pressure Section
4. Pressure-to-Atmosphere Gradient Section

1. The vacuum section consists of a lead-in tube approximately one foot in length with the inside diameter only slightly larger than the nominal core diameter. Immediately adjacent to the tube is a die holder which contains three steel dies with an inside diameter the same as the nominal diameter of the core. (All sections of the apparatus are separated by a die holder equipped with three dies each.)

Adjacent to the lead-in tube is a vacuum chamber 13 1/2" long. Experience indicates the best results are obtained with a vacuum of 25 in. Hg in the chamber.

2. The vacuum-pressure gradient section is a chamber constructed of two concentric tubes 24" long. The small tube inside diameter is sized the same as the lead-in tube while the outside tube forms a heat exchanger with the inside tube. The space between the two tubes is flooded with chilled water (45°F).

This chamber serves to "freeze" any compound that may flow counter to the direction of core travel,

thus preventing any of the filling compound from contaminating the vacuum system. The die holder located between this chamber and the vacuum chamber is heated to 230°F and provided with a drain to remove any filling compound that may flow past the chilled chamber during start-up or shut down.

3. The pressure section consists of a steam jacketed tube approximately 19" long. The filling compound is introduced into the core at this location. The compound pressure and temperature are controlled by instruments in direct contact with the compound. A compound temperature of 210°F $\pm$ 5°F and pressure of less than 5 psi are considered optimum.

4. The pressure-to-atmosphere gradient section is composed of a 36" long heat exchanger consisting of two concentric tubes. Chilled water (45°F) is circulated through this heat exchanger.

The following results have been achieved by the use of this system:

1. To date, the system has successfully filled 50 pair-19 gauge, 100 pair-22 gauge and 200 pair-24 gauge cables. Laboratory tests of degree of fill indicate that pair size, core configuration and line speed have no appreciable effect on ability to fill cores. In fact, 50 pair-19 gauge cores have been filled at line speeds up to 185 fpm. Limitations of the compound system and certain equipment in the sheathing line limited length of run to approximately 1,000 feet and line speed to the 185 fpm.

2. Use of vacuum to remove air from cores allows relatively low pressure to be used for the impregnation system. This low pressure, maximum of 5 psi, allows use of rigid dies and long, close fitting tubes as effective "seals" for containment of the liquid compound and eliminates the potential safety hazards associated with high pressure liquid. The use of the water chiller as the last section of the equipment effectively freezes the filling compound on the periphery of the core preventing loss of compound before a dielectric wrapping is applied.

3. Filling stranded cores in tandem with the sheathing operation at normal line speeds allows continuous operation and restricts handling of the compound to one shop area. The only apparent effect on shop operation is an increase in set-up time required to change dies and tubes in the filling equipment.

4. High temperature flow characteristics of the compound have been retained and tests indicate cables made by this method meet the Bell Telephone Laboratories' design intent.

5. A 50 pair-19 gauge cable with low density polyethylene insulated conductors was manufactured on the subject equipment. Samples of this cable were tested by the Bell Telephone Laboratories as follows:

5. a. Holes were drilled into the sheath of a 10' sample at 1' intervals, care being taken not to penetrate the core wrap. This sample, except for the test ends, was then immersed in a tank with approximately a 3' head of water. Capacitance of 20 pairs was measured immediately after immersion, then repeated after 4, 14 and 22 days. The average increase in capacitance after 22 days was 0.3% which is by far the best result they have observed on any waterproof cable to date.

b. Another evaluation consisted of immersing one end of a sample of cable in the same tank, allowing the unprotected end to lie at the bottom of the tank. After two weeks, the sample was carefully dissected and inspected under a magnifying glass for signs of water. In the core, for the 1' section nearest the exposed end, a few minute droplets of water were detected. Beyond this section there was no sign of water.

This process appears to be the best method to fill cable cores in tandem with a sheathing line due to the demonstrated ability to fill any core size or configuration, low pressure compound handling, no adverse effect on sheathing line speeds, no degradation of the filling compound and excellent capacitance stability of the filled cores.

The cable filling compound must possess several important attributes in addition to being waterproof. Since the filler material replaces the air in the cable, it must have excellent electrical properties so that the increase in wall thickness of the primary insulation need not be excessive to maintain identical transmission characteristics with air core PIC cable. The filler must be available in large quantities (100 million lbs./yr.) at a low cost. Since above ground terminals and closures are used in conjunction with buried cable, the filler material must show excellent resistance to flow at a temperature of 68°C.

Low temperature properties such as adhesion and resistance to cracking are also important as some handling of the cables may be made in winter. Finally, and perhaps most important since installation personnel come in intimate contact with the material, it cannot have any toxic effects and should not be objectionable to handle.

Extensive studies by Bell Telephone Laboratories led to the development of a blend of petrolatum and low molecular weight polyethylene which exhibits all of the above mentioned criteria. The costs of the two raw materials are both low; however, the cost of mixing, handling, shipping and the addition of antioxidant to improve product quality due to the long blending cycles and additional heat history increased the cost by approximately 30%.

Handling and shipping of the compound contributes to an increased cost due to the many problems associated with the compound as opposed to petrolatum. Petrolatum is normally shipped as a hot liquid in insulated tank cars either by truck or rail. The melting point of this material is the 120°F to 150°F range, and considering a 50°F

differential, the shipping temperature should be in the 170°F - 200°F range. Petrolatum can be held at these temperatures for weeks with no measurable loss in electrical properties due to degradation.

Should the petrolatum solidify during transit, it can be remelted easily by using low pressure steam. The melting point of the petrolatum-polyolefin blend is 200°F minimum and, therefore, shipping temperature would be approximately 250°F. At this temperature the kinetic rate of reaction is at least ten times as rapid as at 200°F and even after stabilization with antioxidant, serious deterioration of electrical properties is evident after approximately 100 hours. Should solidification occur, remelting the petrolatum-polyolefin compound would present a paramount problem as localized overheating and subsequent degradation in the immediate area surrounding the heat source is almost a certainty. Thus, it should be concluded that at present there is no method available to economically ship the compound in the molten state without incurring serious electrical degradation in the product.

Shipping the compound cold in drums (or equivalent) is not feasible due to the quantities involved and would present serious handling problems in the shop. Thus, in-plant compounding and blending appeared to be the only economical approach.

At the time it became evident that in-plant mixing must be investigated, petrolatum-polyolefin compound was being manufactured for Western by two suppliers. Both companies used a batch system, i.e., measured quantities of hot petrolatum, pelletized polyethylene and antioxidant were added to a large tank, mixed and discharged into drums. This method possesses several obvious disadvantages to Western. First, cable is manufactured continuously in the plant, thus mixed compound must be available at all times for the filling operation. A storage tank for mixed compound in conjunction with a batch mixer would therefore be required for continuous delivery of compound to the filling units. Secondly, even though a special low melting point high melt index polyethylene is used, approximately a one hour residence time in the mixer is required because the polyethylene must melt before it can mix. The long melting period is encountered because of the low coefficient of heat transfer between the polyethylene pellet and the petrolatum and the small differential between the mixing temperature (265°F) and the "melting point" of the polyethylene (230°F). Due to this long mixer residence time, typical mixer size would be approximately 600 gallons with associated storage tank 50% again as large. During periods when filled cable is not being manufactured in the shop (vacation, three day weekends, etc.) material which had been blended would probably have to be disposed of due to degradation of electrical properties. Aside from being costly, there is no known economical way of disposing of compound in large quantities.

The use of polyethylene powder in place of pellets would substantially reduce the mixer residence time, however, the grinding costs incurred would increase the cost of the compound about .3¢/lb. Maintenance, cleaning and frequent calibration of the weigh dump scales would also detract from the initial attractiveness of powder. Vibrator-feeders or constant volume feeders for ground polyethylene were discounted based upon the large variation in bulk density associated with ground polyethylene. As indicated, most of the time spent in the mixer is directed toward melting the polyethylene.

Studies showed complete mixing was accomplished in minutes when melted polyethylene was introduced into hot petrolatum (265°F) in a small mixer. The most economical method to melt and meter polyethylene is extrusion. An extruder is a very accurate metering device and can provide a continuous flow of polyethylene into a mixer.

With the use of an extruder and a metering pump for the petrolatum, a continuous mixing system should be considered in preference to the aforementioned batch system. In a continuous system, both petrolatum and polyethylene are constantly flowing into a mixer and mixed compound is constantly flowing out at equivalent rates. Due to the increase in mixing efficiency associated with melted polyethylene, the size of a 500 gallon/hr. capacity system could be reduced from 600 gallons (batch mixer with ten minute loading time included) to 50 gallons. The need of a compound storage tank would be eliminated with the use of a continuous mixer. The reduction in volumetric capacity allows changes in the mixture in the range of an extrudable plastic and a petrochemical with no large quantity to discard.

Based on a continuous mixing approach, the following process has been developed (see Figure 2):

Cream white petrolatum is shipped in 55 gallon disposable drums. It is pumped cold from these drums into a 350 gallon hold tank by an air operated piston pump which is suitable for pumping grease. The hold tank is steam jacketed and heats the petrolatum from ambient temperature to 150°F (20-30°F above melting point). The petrolatum is agitated via a marine type impeller driven by a 1/3 h.p. electric motor. Agitation will assure uniformity of temperature throughout and will avoid localized overheating. A vent to the roof is provided on the hold tank to allow petrolatum volatiles (.5-1.8% weight) to escape to the atmosphere.

As production capability is developed, the quantity of petrolatum will require bulk handling.

Petrolatum is continuously pumped from the hold tank to a ten gallon constant head tank located above the hold tank. The ten gallon tank is provided with an overflow return to the hold tank to maintain a constant head for supply to a very accurate variable output diaphragm metering pump. The petrolatum is then pumped through a heat exchanger to increase the temperature from 150°F to 265°F and then is discharged into a mixing vessel.

Low density polyethylene, supplied in 1,000 lb.

pillar packs, is conveyed to a cold water jacketed storage bin above the extruder. The polyethylene is gravity fed to the extruder which delivers molten polyethylene to the mixing vessel.

Variable output in lbs./hr. of petrolatum-polyolefin compound can be delivered at constant concentration by varying the speeds of the metering pump and the extruder in direct ratio since both outputs are linear.

The 50 gallon mixing vessel is steam jacketed to maintain the PE-PJ mixture at 265°F. The vessel is divided into four vertical chambers by annular horizontal baffles to provide three distinct zones of mixing with the top section for level control. A 3 h.p. constant speed motor is mounted above the mixer and drives propellers in each of the three mixing zones. Four equidistant vertical baffles extend the full length of the mixer and are spaced approximately 1/2" from the wall of the vessel to provide additional turbulence and eliminate vortexing in the upper mixing chamber. Vortexing would cause air to be entrained in the final compound. High-low controllers maintain the compound level above the top annular ring and adjust input for variations in compound level.

The blended compound flows by gravity from the bottom of the mixing vessel to steam jacketed pumps which supply the filling equipment.

The key to manufacturing acceptable PE-PJ compound is to maintain uniform and non-varying concentration. If the concentration of polyethylene is too high, the filled cable is too stiff and the compound may crack at low temperatures. If the concentration is too low, the compound may flow at elevated temperatures.

The extruder and metering pump are powered by variable speed drives. The metering pump also has an adjustable stroke. Calibration is accomplished as follows:

With the extruder drive running at maximum rpm, the output can be measured. From this output, the corresponding petrolatum flow rate can be calculated for the desired concentration. The metering pump is then operated at maximum rpm and the stroke adjusted for this flow rate. No further adjustments are necessary unless the composition of the compound is to be changed. Since the outputs of both the extruder and the metering pump are linear with speed, operation at any intermediate flow rate is possible.

Variation in compound usage will cause the level of compound in the mixer to change. A sonar device senses this change in tank level and delivers an amplified signal to a proportioning device. A percentage of the signal from the proportioning instrument is relayed to both the metering pump and the extruder. The percentage of the signal going to each drive controller is dependent upon the maximum speed of each unit and is preset.

Present make-up system capability is severely limited by the small (2") extruder. While the entire compound mixing system is sized for 500 gallons per hour, the present extruder limits system output to 125 gallons per hour. (A 2" extruder was available as surplus equipment.) Since nominal line consumption is about 100 gallons per hour, level control in the mixing tank is maintained between a high and low point in the upper chamber of the mixer by running the extruder and metering pump in full on and full off position.

Samples of current production have demonstrated the composition of the compound can be maintained with $\pm$ 1% of the target concentration. No degradation of either electrical or physical parameters has been detected in any compound made to date. Homogenity of the blend is better than any commercially available material. Consequently, the blend shows greater resistance to flow at elevated temperatures than commercial material and cables filled at Baltimore have far exceeded the Laboratories' requirement in this area.

Because of the direct relationship between viscosity and concentration, the use of a viscosity monitor and controller is being investigated to provide a more exact control of the composition of the compound.

The following results have been achieved with the use of in-plant compounding system:

1. The cost of the compound has been reduced as low cost raw materials are automatically blended and fed to the filling station. The only labor required is to provide the two materials to the system using conventional bulk handling methods. The use of an antioxidant to reduce thermal degradation of electrical properties can be eliminated. A different antioxidant may be required by the Laboratories for stabilization of the primary insulation.

2. The petrolatum-polyolefin blend product quality has been markedly improved. The heat history of the compound has been eliminated because the compound is used as soon as it is made. The previous method of manufacture involved the supplier making the compound and shipping it cold in drums which required reheating the material prior to use. The above improvement has eliminated the need of an antioxidant for thermal protection which in turn improves the electrical properties of the blend. Homogenity of the blend has been greatly improved by the use of a small size high intensity three stage mixer. Good homogenity improves flow characteristics at elevated temperatures. For comparison of results of these methods, see attached Table 1.

This in-plant compounding system has been used to produce approximately eight miles of field trial cable and various experimental cables with excellent results.

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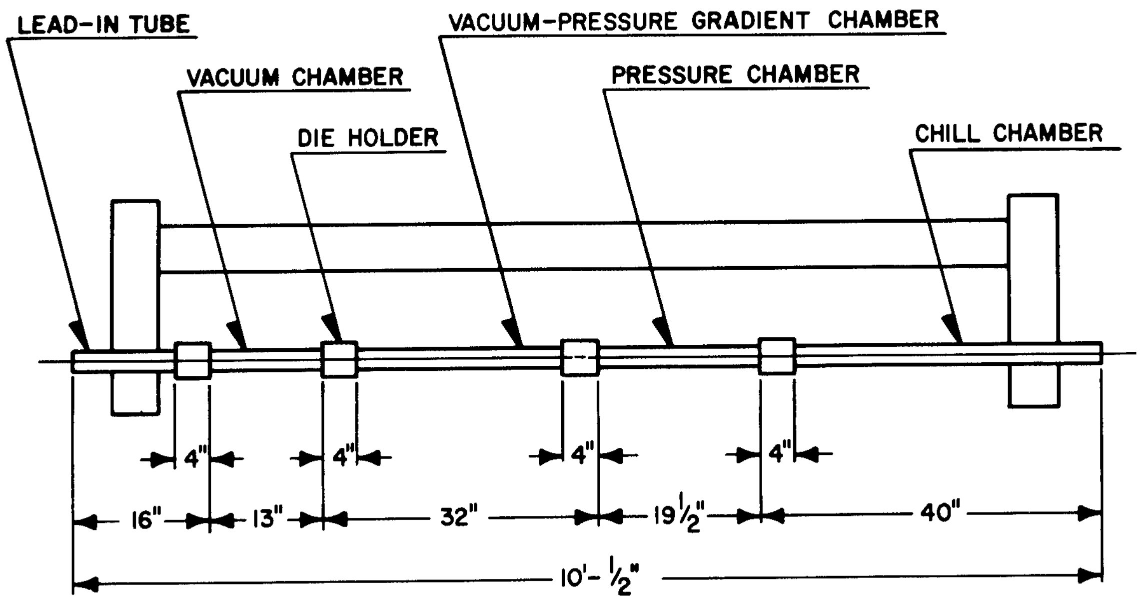
Edward L. Franke, Jr. is presently a Senior Engineer in Cable Sheath Development at Western Electric, Baltimore, Maryland. Since joining W.E. in February, 1952, he has spent 11 years in cord engineering; and his cable assignments have included wire drawing, die room, annealing furnace and cable sheathing. Currently his assignments are waterproof cable, lead-free sheath for coaxial cable and moisture resistance sheath for exchange cable. Mr. Franke has been issued 4 patents with 2 patents pending. He graduated from the University of Maryland with a B.S. degree in Mechanical Engineering.

TABLE 1

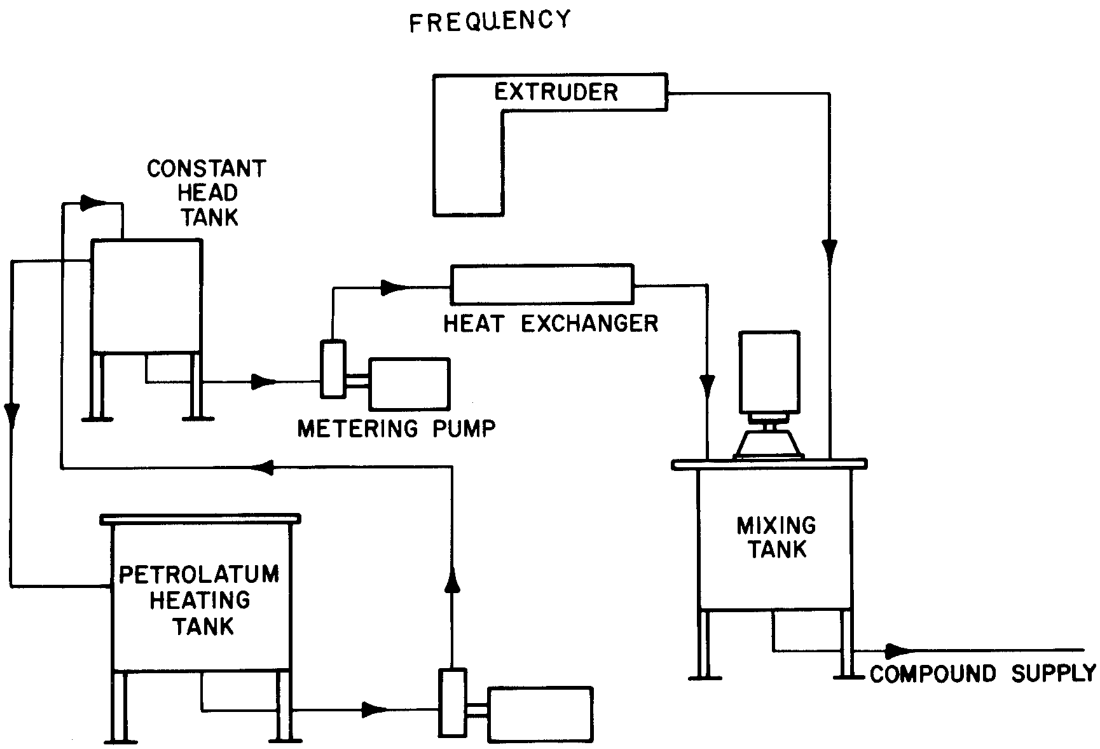
		Supplier A Pure Petrolatum	Compound Made at Baltimore from Supplier A Petrolatum	Compound Made at Baltimore from Supplier A Petrolatum on a Different Date	Values per W.E. Specification 62072
Dielectric	10^5	2.18	2.23	2.15	2.25
	10^6	2.18	2.24	2.15	2.25
Dissipation	10^5	.00024	.00027	.00040	.0004
	10^6	.00090	.00085	.00087	.0010

		Supplier B Pure Petrolatum	Compound Made at Baltimore from Supplier B Petrolatum	Compound Made at Baltimore from Supplier B Petrolatum on a Different Date	Values per W.E. Specification 62072
Dielectric	10^5	2.15	2.19	2.17	2.25
	10^6	2.15	2.20	2.18	2.25
Dissipation	10^5	.00024	.00020	.00013	.0004
	10^6	.00083	.00068	.00052	.0010

Electrical properties of two suppliers' petrolatum and compounds made from them in the continuous process at Baltimore.



VACUUM-PRESSURE IMPREGNATION EQUIPMENT



COMPOUND MIXING SUPPLY EQUIPMENT

PREFABRICATED PRESSURE DAM FOR TELEPHONE CABLE

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Summary

In gas pressurized telephone cable systems, a pressure dam is needed at each end of the gas sections. In order to resolve problems of imperfect gas-tightness encountered in making the pressure dam in the installation site, a cable with prefabricated pressure dam prepared uniform factory conditions has been developed.

The introduction of prefabricated pressure dam cables has greatly improved the reliability of pressurized cable systems and also much reduced man hours of installation work.

Introduction

Gas pressurized telephone cable systems with dry air or dry nitrogen have been recognized to be very effective to monitor and localize sheath breaks or faulty joints, and to prevent the entrance of moisture through them. The effectiveness depends on gas pressure stability in the pressurized cable section. This means that gas sections must be virtually leak-free, above all, pressure dams furnished at each end of the gas sections must be air-tight.

Today, most underground cable of NTTPC (Nippon Telegraph and Telephone Public Corporation) maintained under gas pressure protection. Pressure dams provided at junctions of pressurized feeder cable to non-pressurized distribution cables have been made in the field using an epoxy compound. Field-made pressure dams are not only man hours consuming but susceptible to gas leaks.

According to the examination by dissolving leaky pressure dams, the following were found as causes of the gas leakage.

(1) Cracks or congregation of air bubbles created during curing process being caused by change of ambient temperature and vibration due to road traffic.

(2) Cracks or tiny gaps due to the difference of thermal expansion coefficients between the epoxy compound, conductor insulation, lead sleeve and other components of the pressure dam and cable.

(3) Poor adhesion between the epoxy compound and polyethylene.

(4) Errors in weighing out the proper ratio of epoxy resin and hardner according to the ambient temperature.

It was expected that the use of an epoxy compound with short curing time would save man hours of installation time and also reduce the possibility of gas leakage with less change of vibration due to road traffic. Particularly in cold climate regions, where it takes a fairly long time to make a pressure dam due to cold ambient temperature, an improvement was earnestly required.

In choosing epoxy damming compounds to make pressure dams, however, if an excess amount of hardner is used, an excess heat of reaction is usually generated resulting in insulation damage in the case of polyethylene insulated cable. Leaky pressure dams caused by adverse vibration due to road traffic are unavoidable whenever pressure dams are made in the field. Furthermore, the repair of a leaky pressure dam itself is very difficult. The only ways to repair the leakage are, generally, to replace the faulty pressure dam with associated cable or to make another pressure dam close to the faulty one.

The resolution of all the problems mentioned above, by development of a new filling compound or improvement in the method of making pressure dams, was realized to be very difficult. From this situation, the development of a prefabricated pressure dam cable, a relatively short length of cable with built-in pressure dam, has been undertaken. Since prefabricated pressure dams are factory-made and tested under good and stable circumstance, they were expected to have high reliability with the additional advantage of saving man hours of installation.

Development of pressure dam cable

Requirements for pressure dam cable

Factory-made pressure dam cables are, first of all, required to be perfectly gas-tight. Simultaneously, they must have enough mechanical strength to withstand shock and vibration during transportation, and also tension and bending during installation. In addition, the life of pressure dams has to be as long as the associated cables under vibrations due to traffic, ambient temperature change and other environmental conditions. Upon the development of pressure dam cables, taking the above requirements into account, the test requirements shown in Table 1 were established.

Construction and methods of making the pressure dam cable

Test requirements given in Table 1 are quite severe. In many tests performed on pressure dams made by conventional methods, injecting generally available epoxy or polyurethane compounds, most of the dams were not able to keep gas-tightness after a few cycles of the temperature cycle test.

Even with factory-made pressure dams, of course, there are several problems to be overcome. The most important problem is how to avoid leaky gaps caused by poor adhesion between the polyethylene and damming material or the difference of thermal expansion coefficients between damming material and other components in the pressure dam. Various constructions and composing materials can

be considered for making pressure dams depending on the method used to prevent the possibility of leakage.

Three types of pressure dam described herein-after, resulted from extensive trial work, have different constructions and materials respectively, but all of them have excellent gas-tightness conforming to all the test requirements in Table 1.

Type A pressure dam (See Fig. 1)

The principle of stopping gas leakage in the Type A pressure dam is as follows. Leaky gaps between the different materials in the pressure dam, created by thermal expansion and contraction due to temperature changes, are eliminated by the spring action of a resilient body. Gaps between the conductor insulation and filling compound are also avoided by this function. A filling compound, used in this method, must have suitable elasticity and hardness to enable it to follow and transfer the resilience of the resilient body. That is the reason why a polyurethane compound is used in the Type A pressure dams.

To make the Type A pressure dam, the cable sheath, wrapping tape and bindings on conductor units are removed from a short section of the cable, then the cable core is loosened to enable the spread of the filling compound into every gap between the conductors. After a thin pipe of resilient material with a longitudinal slit is placed over the sheath opening, the slit is wedge opened

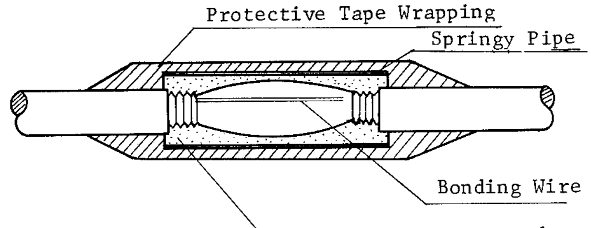

FIG. 1 TYPE A PRESSURE DAM

TABLE 1. TEST REQUIREMENTS FOR PRESSURE DAM CABLE

Test Item	Requirements
Temperature cycle test	Dams are subjected to 100 cycles of temperature variation from +70°C to -30°C with 2 hour period.
Vibration test	Dams are vertically fixed at upper end, and a vibration of 10 mm amplitude and 300 cycles per minute is given at the lower free end for 10^6 cycles.
Low temperature test	After one cycle of the temperature cycle test, dams are kept at -30°C for 2 hours, then subjected to the vibration test for 10^5 cycles at room temperature. This test is repeated 5 times.
Drop test	Dams held horizontally are dropped on a concrete floor from a height of 2.5 meters.
Impact test	A 1.5 Kg iron ball is dropped on the dam from a height of 5 meters.
Bending test	One end of cable of 1 meter long adjacent to the dam is bent 5 times at an angle of 45 degrees on both sides of axis of the dam.
Static load test	A 110 Kg or 210 Kg (1,200 pair cable only) weight is hung onto one end of the dam for over one year.
Tensile test	Dams are subjected to a tensile stress of 500 Kgs at a pulling speed of 100 mm per minute.
Gas pressure test	Dams are kept under gas pressure of 1 Kg/cm^2 at -30°C in all of the above tests.

giving some expansion to the pipe. As a final step, the polyurethane compound is injected into the dam portion, and the wedges are removed after curing of compound to recover the resilience of the springy pipe. (See Fig. 2) This type of pressure dam is rather heavy due to the use of a steel springy pipe, but relatively compact.

Type B pressure dam (See Fig. 3)

The Type B pressure dam achieves gas-tightness by injecting low density polyethylene, as a damming material, into the cable core of the polyethylene insulated conductors. Since this type of pressure dam is homogeneous in composing materials except for the copper conductor, excellent gas-tightness is obtained because of little possibility in creating leaky gaps between the materials in the dam.

In making the Type B dam, an exposed and loosened cable core in the same way as type A is enclosed in a moulding case then preheated. After preheating, low density polyethylene is injection moulded into the cable core, and the moulded dam is covered with a protective sleeve. Conductors in the dam are separated enough from each other to enable uniform injection of polyethylene resin. This arrangement causes the dams to have a rather large diameter.

Type C pressure dam (See Fig. 4)

In this type, a newly formulated epoxy compound is filled and squeezed into the cable core, and hardened under pressure. Polyethylene insulated conductors with special surface treatment are used so as to obtain satisfactory adhesion between conductor insulations and the epoxy compound. Another protective mould of a polyurethane compound is provided over the epoxy moulding. As the cable core with the filling compound is squeezed to force air-gaps and bubbles out, pressure dams with thinner diameter are obtained by this method.

Each of these three types of pressure dam have merits and demerits, however, they have good enough functions as pressure dams. Since there was no difference in the convenience of installation work among the three types of dam, no necessity to standardize the type of pressure dam existed. Consequently, all of the three types of pressure dam have been allowed in the specification and put to use.

Kinds of pressure dam cable

Pressure dam cables for rising points, where feeder cable and distribution cable are jointed, are CCP Stalpeth® cables with 1200 or less pairs provided with a factory-made pressure dam. Cable sizes have been standardized to 400,800 and 1,200 pairs of 0.4mm conductor only for easy supply and simplified plant design. From experience, cable lengths have been also standardized to four fixed lengths of 20, 25, 30 and 40 meters with options for longer cables than 40 meters to actual requirements.

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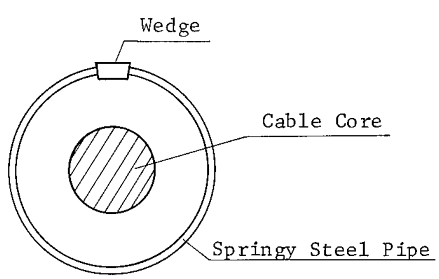
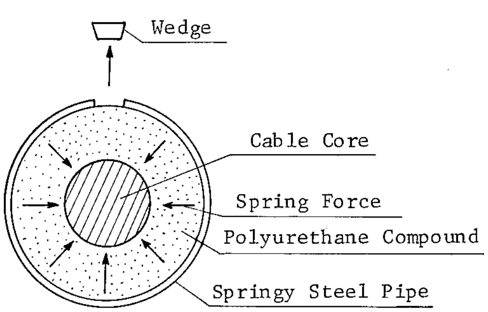


a) Before Polyurethane Injection



b) After Curing of Polyurethane

FIG. 2 FUNCTION OF SPRINGY PIPE

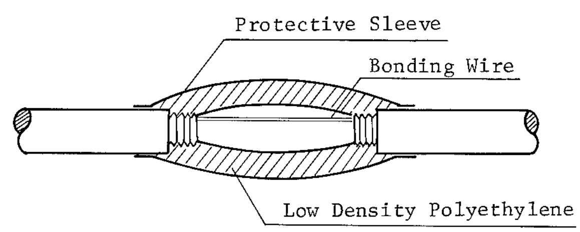


FIG. 3 TYPE B PRESSURE DAM

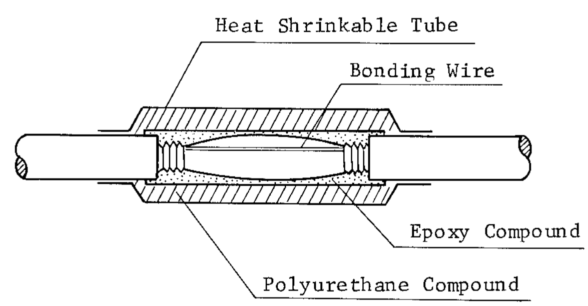


FIG. 4 TYPE C PRESSURE DAM

The kinds of cable and their dimensions are shown in Table 2. The maximum dimensions of completed pressure dams have been specified as given in Table 3 for the convenience of installing the pressure dams vertically along telephone poles.

Field tests of the pressure dam cable

The factory-made pressure dams proved their excellent performance as a gas dam passing through various accelerated aging tests. However, as the pressure dams have larger diameter and lower yield strength than those of associated cables, the cables with a dam cannot be pulled through underground ducts. This situation limits the method of installation to a certain extent. For instance, while rising cables are usually pulled into underground ducts towards rising poles, cables with a dam have to be installed from rising poles towards underground ducts.

There was concern that this limitation may complicate and hinder installation work. Then, field tests to confirm the feasibility of installation work were conducted using about 40 pressure dam cables of various lengths. The test results proved that the convenience of installation work of pressure dam cables was the same as that of ordinary cables. It was true with the restriction of pulling direction and even in case of the telephone poles with a platform or distribution cabinet. Furthermore, no special tools were needed for the installation.

The pressure dam itself and the cable portion close to the dam is not so flexible that conventional cable drums can be used for storage and transportation. New type of drums, therefore, have been developed suitable to accomodate and protect several pressure dams and associated cables on a single drum allowing easy winding and unwinding.

Electrical properties

The pressure dam cables have the following electrical properties at 20°C.

Conductor resistance: The DC resistance of any conductor is nominal 139.0Ω/Km, and not more than 147.5Ω/Km at maximum.

Dielectric strength : The insulation between any conductor and all other conductors, aluminum tape and steel tape tied together and grounded, is capable of withstanding a DC potential of 500 volts or AC 350 volts of 50 Hz or 60 Hz for one minute without breakdown.

Insulation resistance: The insulation resistance between any conductor and all other conductors, aluminium tape and steel tape tied together and grounded is not less than 10ΩKM . The measurement is made with a DC potential of not less than 100 nor more than 500 volts applied for from 1 to 3 minutes.

Mutual capacitance: The average value of mutual capacitances of each length is not more than 5.5 nanofarads per 100 meters as measured at a frequency of 1 KHz.

Future view of pressure dam cables

The introduction of the pressure dam cables to jointing points of the pressurized feeder cable and non-pressurized distribution cable has highly elevated the reliability of pressurized cable systems as well as saved man-hours of installation work. These pressure dam cables were first put into field service in January 1971 in cold climate area. After the production capacity of the manufacturers had expanded, the application was spread throughout the country in September 1971.

Pressure dams are also made at terminations of feeder cable in exchange offices, and are prepared by injecting compound into cable joints at installation site. Attempts were made to make pressure dam cables for the termination with similar requirements as those for rising cables. The result of the studies has showed that the same methods are applicable to this purpose. At present, several trial pressure dam cables of full size for termination are being field tested. The cable termination in exchange offices needs a valve for pressure gas charging, and pressure dam cables with a gas valve built into the dam itself have been developed. If field tests on pressure dam cables for termination with a built-in gas valve give satisfactory results, the built-in gas valves will also be applied to pressure dams for rising cables.

Conclusions

The introduction of prefabricated pressure dam cables has highly improved the reliability of pressurized cable systems, also largely saved man hours of installation work. Further studies are being made to make pressure dams more neat and compact and to rationalize methods of packing and transportation.

Acknowledgement

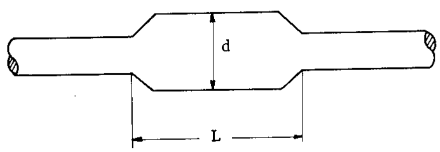
The authors wish to express their sincere gratitude to engineers of Fukurawa Electric Company, Ltd., Sumitomo Electric Industries, Ltd., and Fujikura Cable Works Ltd. for their assistance during the development of the pressure dam cables.

TABLE 2. KINDS OF CABLE AND THEIR DIMENSIONS

Cable Size (mm-pair)	Actual No. of pairs	Nominal Dia. of cable core (mm)	Average thick of PE sheath (mm)	Overall Dia. of cable (mm)
0.4 - 400	400	32	Min. 1.5	39
0.4 - 800	800	44	" 1.9	53
0.4 - 1,200	1,200	51	" 2.0	60

TABLE 3. DIMENSIONS OF PRESSURE DAM

Cable Size (mm-pair)	Length L (mm)		Diameter d (mm)	
0.4 - 400	Max.	700	Max.	85
0.4 - 800	"	800	"	105
0.4 - 1,200	"	800	"	125



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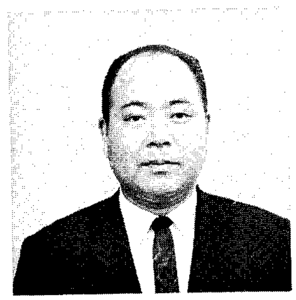

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SZ TWISTING AND STRANDING OF COMMUNICATIONS CABLES USING ROTATING ACCUMULATORS WITH PERIODICALLY CHANGING CAPACITY

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Summary

This paper deals with the SZ method with "breathing" double accumulators which is characterized by the completely uniform rotational movement of the accumulator arrangement and the constant inlet and outlet speeds of the material to be twisted and stranded. It allows high-speed star quad twisting and unit stranding in one single operation (about 100 m/min) without applying special adhesives at lay reversal points.

Introduction

The economy of the manufacture of communications cables is being increasingly affected by rising personnel expenses. In order to counteract this development there is in the field of communications cables stranding the tendency to combine several upto now separate twisting and stranding operations in one single operation(Fig.1) and to save in this way a part of that labor which has so far been necessary for the time-consuming exchange of reels.

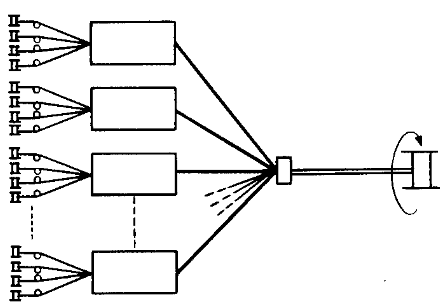

Fig. 1 Combined twisting and stranding operations

One method for the combination of operations is the SZ twisting and stranding, i. e. the twisting and stranding with section-wise reversing direction of lay (Fig. 2)[1,7,8,16].

It can be carried out between stationary pay-off and take-up stands. Only a minor part of the material to be twisted and stranded needs to swing around the stranding axis or to be encircled by a stranding flier. In principle, it is therefore possible to combine as many twisting and stranding operations as one likes or even to link them up with the core manufacture or sheathing operations by using relatively light twisting and stranding devices.

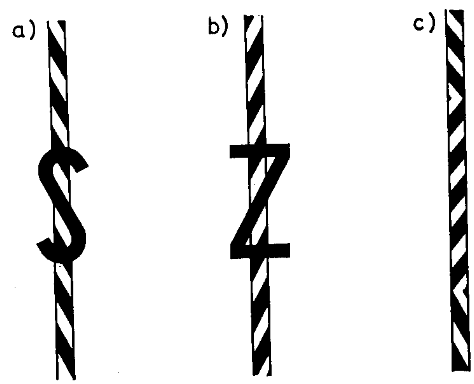

Fig. 2 Origin of the term "SZ Stranding"
a) S twist b) Z twist c) SZ twist

SZ Twisting and Stranding of Local Cables

The application of the SZ twisting and stranding method is particularly economic with regard to the manufacture of local cables. Today, the bunching technique gains more and more ground for the production of these cables. In view of the desired good electrical and mechanical properties as well as for reasons of identification and installation, in most cases the following make-up elements are chosen for multi-pair cables (Table 1):

A	pairs or star quads
B	basic units, e.g. made up of 25 pairs or 5 quads
C	main units, e.g. made up of 4, 5, 6 or 10 basic units
D	cable core, made up of several main units

Table 1: Make-up elements in unit-stranded local cables

The Western Electric Co. were the first to apply on a large scale the SZ stranding method for the combined basic unit and main unit stranding[2], i. e. the combined manufacturing of B and C. A swinging lay plate operating with alternating direction of rotation is used[3,4] by which, for example, 25 pairs are combined to one basic unit with reversing direction of lay (Fig. 3).

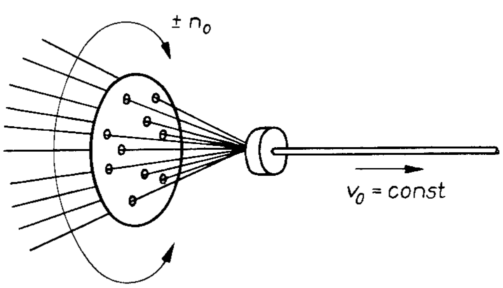

Fig. 3 SZ stranding using a rotating lay plate

This method which could be further improved by the employment of several lay plates[5] distinguishes by a reversal of the direction of lay after every stranding lay or after several stranding lays each. Thus in many cases a sufficient decoupling of neighboring units is given. For higher demands regarding the elimination of crosstalk, the Siemens AG has developed a suitable process[6] where the strand is run straightened freely through the air over several meters and is twisted section-wise in reverse directions by means of an alternately rotating stranding support (Fig. 4). In this way, for example, sections of 10 m length with constant direction of lay are produced. This method has well proved for the combined basic unit and main unit stranding of PE insulated local cables composed of pre-fabricated star quads, i. e. also for the combination of B and C as shown in Table 1.

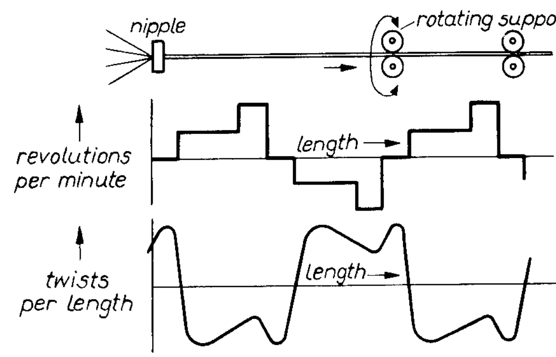

Fig. 4 SZ method using a rotating stranding support

To realize by which twisting and stranding operations the most manpower can be saved let us look at the case of a production consisting of separate operation steps, A to D. Approximately, the following labor would be needed:

operation	A	B	C	D
manufacture of	pairs or quads	basic units	main units	cores
percentage of machine operators	55 %	25 %	10 %	10 %
sum	100 %			

Table 2: manpower demand for separate twisting and stranding operations

combination of twisting and stranding operations	A + B	B + C	C + D
	pair or quad twisting and basic unit stranding	basic and main unit stranding	main unit and core stranding
saving of operators	40 %	17 %	out of consideration

Table 3: Saving of manpower with combined operations (100 % = total personnel demand for separate twisting and stranding operations)

When combining two operations, the exchange of the reels is once avoided for each operation so that - as experience shows - only about half the number of operators would be required. The combination of A and B results in a personnel requirement of only 40 % for both these operations as against 55 % + 25 % = 80 % in the case of separate operations.

Table 3 shows that it is highly attractive to combine the pair or quad twisting with the next following stranding operation even if a large capital expenditure for machinery would be necessary. This applies all the more since further wage rises can be expected in the next years and it will become more and more difficult to compensate this increase of costs. That is why manpower-saving manufacturing methods will be of ever-increasing importance in future.

In the following those SZ methods are treated that are suitable for the combination of pair and quad twisting respectively with basic unit stranding.

SZ Methods for Twisting Pairs or Star Quads

SZ Pair Twisting

As far as we know, the twisting of wire pairs according to an SZ method and bunching of these pairs in one single operation has so far been carried out only in Germany (by Siemens AG). The thus treated cables are not local cables but PVC insulated switchboard cables with 0.4 to 0.6 mm conductor diameter. The previously mentioned method as illustrated in Fig. 4 is applied[6]. 10 wires are supplied from stationary pull-off stands to 5 twisting nipples and are parallely twisted to 5 pairs by simple twister tools (Fig. 5). These pairs are fed to a unit stranding nipple and conventionally bunched during same operation. A characteristic feature is the

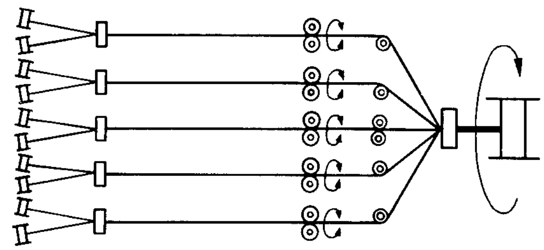

Fig. 5 Combined pair twisting and bunching similar to Fig. 4

very long section between pair twisting nipple and twister tool where the pair involved is already partly twisted. The pull-off speed amounts at present to 70 m/min and can be further increased. This SZ twisting has proved very well in the normal manufacture. The same method is also applied for the twisting of elements composed of 3 or 5 wires to switchboard cables.

SZ Star Quad Twisting

Plastic insulated local cables for the German Post Office consist of basic units with 5 quads each. 5 or 10 basic units are stranded to main units and subsequently to the cable core.

For this reason, there is much interest in Germany as well as in other countries in an SZ method being suitable for quad twisting. The application of such methods has been reported in the literature[7,8]. The solutions described there distinguish by the employment of a roller-type accumular arrangement with constant take-up capacity which changes periodically its direction of rotation (Fig. 6a) or which

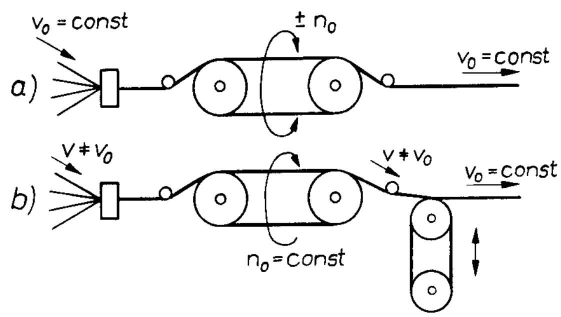

Fig. 6 Star quad twisting methods using an accumulator with constant take-up capacity

is operated with periodically alternating pull-off speed (Fig. 6b)

Both these methods involve the risk that the twisted quad will disintegrate in the neighbourhood of the lay reversal points. For this reason, mostly an adhesive is applied at the reversal points for which an additional equipment is required.

It has been our aim to develop an SZ quadding method where speeding and slowing-down problems - also at high output rates - are only of minor importance and where the danger of untwisting at reversal points does virtually not exist. Such an SZ method is being presented here.

A characteristic feature is the employment of a rotating accumulator with continuously increasing or decreasing take-up capacity, the so-called "breathing" accumulator. The basic idea of a single "breathing" accumulator has been drafted independently of each other in the United States, in Japan, Germany, and Great Britain during the years from 1965 to 1967 and patents have been applied for respectively[9,10,11,12]. The basic concept has been further developed to the especially effective "breathing" double accumulator arrangement (Fig. 9) which allows practically uniform operation like conventional twisting or stranding machines[13,14].

SZ Twisting and Stranding by Means of Breathing Accumulators

Principle Idea

The elements to be twisted or stranded are fed over a stranding nipple to an accumulator uniformly rotating at a speed n and constantly increasing or decreasing its capacity (Fig. 7). In the most simple

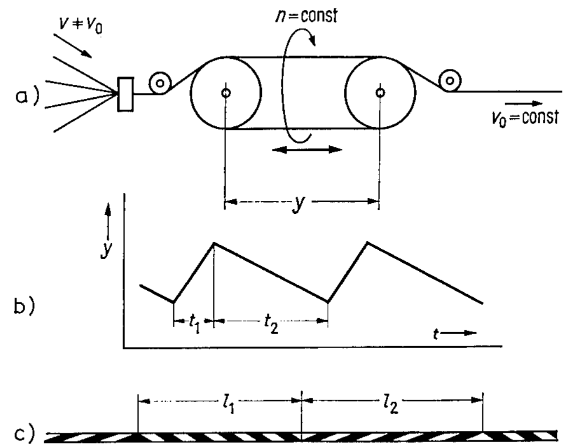

Fig. 7 SZ twisting or stranding using a single accumulator with periodically changing capacity

case the change in the accumulator capacity takes place periodically and sectionwise linear according to a saw-tooth function (Fig. 7b). Let the pull-off speed at the accumulator outlet be designated v_0. As a result of the continuous change in the accumulator capacity the inlet velocity changes between two values different from v_0. Since the rotational speed is constant, sections with different lengths of lay but with equal direction of lay are alternating within the accumulator.

When leaving the accumulator the already existing alternating twist is superimposed by a constant reversing twist. Therefore, the finished twisted strand leaving the accumulator reverses its direction of lay periodically at intervals of l_1, l_2 (Fig. 7c) which means that it is SZ stranded.

By changing the accumulator back and forth movements, the lenghts of lay within the accumulator and after leaving the accumulator can be chosen generously. Useful parameters for dimensioning are the quotients l_1/l_0 and l_2/l_0 respectively, where

l_0 = max. changing rate in accumulator capacity

l_1 = length entering the accumulator during capacity increase

l_2 = length entering the accumulator during capacity decrease.

For the quad twisting, the use of the parameter

$$l_1/l_0 = l_2/l_0 = l/l_0 = 2{,}0$$

has proved functional. Thus, a constant length of lay over the whole length of the finished quad is obtained:

$$s = \pm \frac{l}{l_o} \cdot \frac{v_o}{n} = \pm 2 \frac{v_o}{n}, \qquad (1)$$

with alternating signs. Since two rotations of the accumulator produce one length of lay, this method can be designated as a "half-twist" method.

For the lengths of lay within the accumular, the following equations apply:

$$s' = \frac{-1}{1-l_o/l} \cdot \frac{v_o}{n} = -2{,}0 \frac{v_o}{n} \qquad (2)$$

or

$$s' = \frac{-1}{1+l_o/l} \cdot \frac{v_o}{n} = -0{,}66 \frac{v_o}{n}. \qquad (3)$$

It is shown that these lengths are not longer than the final lengths of lay as per Eq. (1).

Since also the direction of lay does not change within the accumulator, a crossing of wires in the accumulator can be avoided reliably.

In our special case, the times of the accumulator capacity increase (t_1) and capacity decrease respectively are

$$t_1 = \left(\frac{l}{l_o} - 1\right)\frac{l_o}{v_o} = \frac{l_o}{v_o} \qquad (4)$$

and

$$t_2 = \left(\frac{l}{l_o} + 1\right)\frac{l_o}{v_o} = 3 \frac{l_o}{v_o}. \qquad (5)$$

In the case of an accumulator where the maximum capacity changing rate is l_o=2.5 m and v_o = 50 m/min the following cycle of accumulator capacity change results:

$$t_1 + t_2 = 4\, l_o/v_o = 0{,}2 \text{ min.} \qquad (6)$$

The principle shown in Fig. 7 can be applied without additional measures, if the elements to be twisted or stranded can be pulled off supply stands (e. g. barrels) practically inertialess with alternating speeds. If conditions are different, it is possible to pre-connect a second but non-rotating accumulator A to the rotating accumulator B which changes its capacity in reverse direction but at same rate as the rotating accumulator B. In this case, the elements to be twisted or stranded enter the first accumulator at same constant speed as they leave the second accumulator (Fig.8).

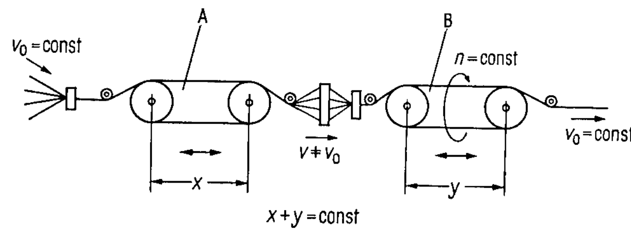

Fig. 8 SZ twisting or stranding with two complementary accumulators (only one rotating) changing their capacities

It is, of course, also possible to interchange the functions of A and B.

Contrary to SZ methods with constant accumulator capacity, the modulation of movements of the accumulators illustrated in Figs. 7 and 8 need not be carried out periodically. The stranding operations at the accumulator inlet and outlet must not be in tune with each other. The movements could, for example, also be modulated according to a law of probability in order to avoid periodic occurrence of lay reversal points which could impair transmission at higher frequencies (e. g. when PCM transmission is applied).

Extension to the Double Accumulator Arrangement Rotating in Inverse Direction

As mentioned before, there is at the lay reversal points a danger of disturbing the geometry of the twisted or stranded group - involving above all the star quadding. In order to keep the influence on the electrical unbalance small one aims at providing for large intervals (l_1, l_2) between the lay reversal points. This leads to the desire to have the largest possible accumulator capacity changing rate l_o, i. e. to use very large accumulators. On the other hand, for reasons of efficiency, small rapidly rotating accumulators are desired.

Both wishes lead to the concept shown in Fig. 9 to use t w o SZ accumulators C and D rotating in opposite directions and changing their capacities inversely. As shown in the arrangement of

Fig. 8, the constant speed at which accumulator C is entered corresponds to the speed at which accumulator D is left. Using the same rotational speed n, the same pull-off speed v_o and identical maximum capacity changing rates l_o for each accumulator the same lengths of lay but double a lay reversal cycle $L=(l_1+l_2)$ as against the cases presented in Fig. 7 or 8 can be obtained.

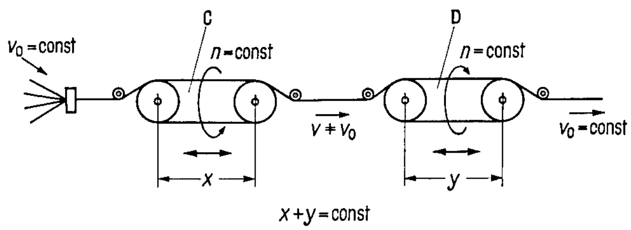

Fig. 9 SZ twisting or stranding with two accumulators with changing capacities rotating in opposite directions

Here, too, we employ the parameters l_1/l_o and l_2/l_o for an appropriate dimensioning. The symbol l_1 signifies the length which enters accumulator D during the period of capacity increase in this accumulator whereas the length l_2 refers to the period of capacity decrease in the accumulator D.

For star quad twisting it has proved practical to use $l_1/l_o = l_2/l_o = l/l_o = 4.0$. Thus, the length of lay of the finished star quad can be expressed by the equation:

$$s = \pm \frac{l}{2l_o} \cdot \frac{v_o}{n} = \pm \frac{v_o}{n} \qquad (7)$$

Within accumulator C the length of lay is given by the equation:

$$s_C = + \frac{v_o}{n} \qquad (8)$$

For accumulator D, it applies:

$$s_D = - \frac{1}{1-2l_o/l} \cdot \frac{v_o}{n} = - 2,0 \frac{v_o}{n} \qquad (9)$$

or

$$s_D = - \frac{1}{1+2l_o/l} \cdot \frac{v_o}{n} = -0,66 \frac{v_o}{n} \qquad (10)$$

It is remarkable that there is only o n e direction of lay within each accumulator. Lay reversal points do not run through the accumulators but are formed only when leaving the last accumulator. Therefore, crossing of wires within a star quad can be reliably avoided also with the double accumulator arrangement.

For the times t_1 and t_2 of the accumulator capacity increase and decrease, Eqs. (4) and (5), which were given for the single accumulator arrangement, are valid.

Performance of Two Different Types of Twisting or Stranding Operations with Complementary Accumulators of Changing Capacities

As mentioned before, the SZ method is suitable for producing e. g. five star quads in one single operation and to strand these immediately to a basic unit. The method using "breathing" accumulators offers a special possibility (Fig. 10): Four wires each are twisted to star quads by means of five single accumulators E with changing capacities and constant rotational speed. Five such star quads are led to a stranding nipple and to a further rotating single accumulator F with changing capacity which they finally leave as a finished basic unit. The changes in capacities of the parallelly arranged quadding accumulators E are tuned to the change in capacity of F in such a manner that the speed at which the quadding accumulators E are entered and the speed at which the basic unit leaves accumulator F are constant and identical. This means that constant inlet and outlet speeds are obtained within the entire arrangement by using a particularly small number of rotating accumulators.

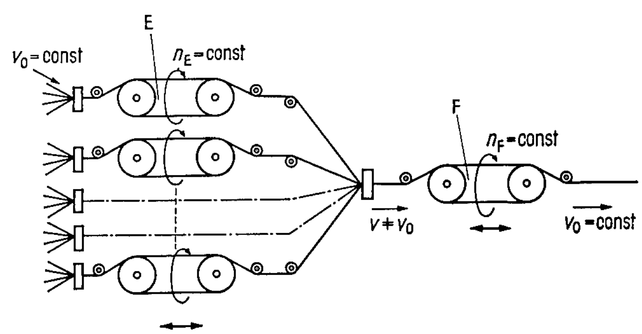

Fig. 10 The combination of two different twisting or stranding operations using complementary accumulators with changing capacities

Favorable Constructional Principles

Since two accumulator rotations are

necessary for one length of lay, the SZ twisting and stranding method with "breathing" accumulators operates with relatively high rotational speeds. In order to obtain large outputs despite this fact, the accumulators are designed such that the constantly rotating mass is kept very small. The constructional elements required for the accumulator capacity increase and decrease are arranged in such a manner that they need not rotate around the stranding axis.

Fig. 11 shows a similar arrangement. The accumulator consists of two roller groups G and H which are pivoted in two frames I and K. Only the roller groups G and H and their holding devices revolve around the stranding axis, thus allowing a rotational speed of at least 3,000 rpm.

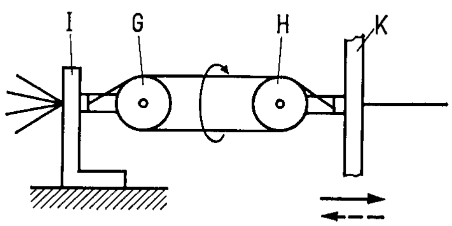

Fig. 11 An advantageous constructional principle

One of the two frames I or K carries out a movement to and fro towards the stranding axis by which the change in the accumulator capacity is effected. Even if the direction of large masses is reversed towards the stranding axis, their acceleration is not critical since the movements towards the stranding axis are very slow. Four to six windings per accumulator have proved favorable.

Fig. 12 shows such an arrangement with several double accumulators operating in parallel. Only the middle frame L moves to and fro relatively slowly thereby changing inversely the capacities of the roller-type accumulators shown at the left and right in the illustration. The to and fro movements of the middle frame L can, for example, be carried out by using a cross threaded spindle.

Experience shows that the centrifugal stress acting on the star quads or units within the accumulator frequently limits the machine speed. Here, it is advantageous to employ accumulators where the material to be twisted or stranded - as

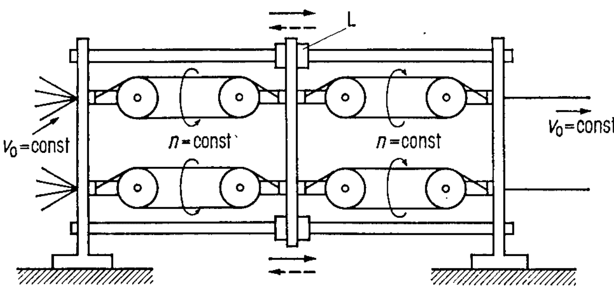

Fig. 12 Double accumulators operating in parallel with common control of the accumulator capacity

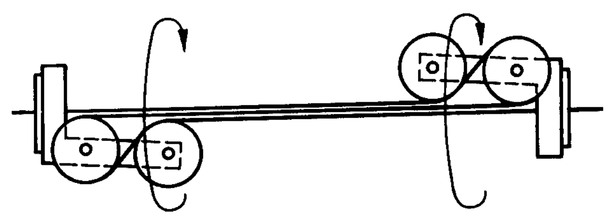

Fig. 13 Accumulator with reduced centrifugal stress on the material to be twisted or stranded

far as it moves freely through the air within the accumulator - is run in the immediate neighbourhood of the twisting axis so that a centrifugal stress does no longer exist. An example is given in Fig. 13.

Application Examples

Quadding Equipment

A five-fold quadding equipment as shown in Fig. 12 has been developed by which 20 plastic or paper-insulated wires with 0.4 mm conductor diameter can be twisted to 5 star quads in one parallel operation (Fig. 14). The equipment is designed such that it can be pre-connected to any bunching machine so that - beginning with single wires - basic units can be produced in one single operation.

The wires are pulled off supply reels (not shown in the illustration) "overhead" with constant pull-off speed v_0 and run

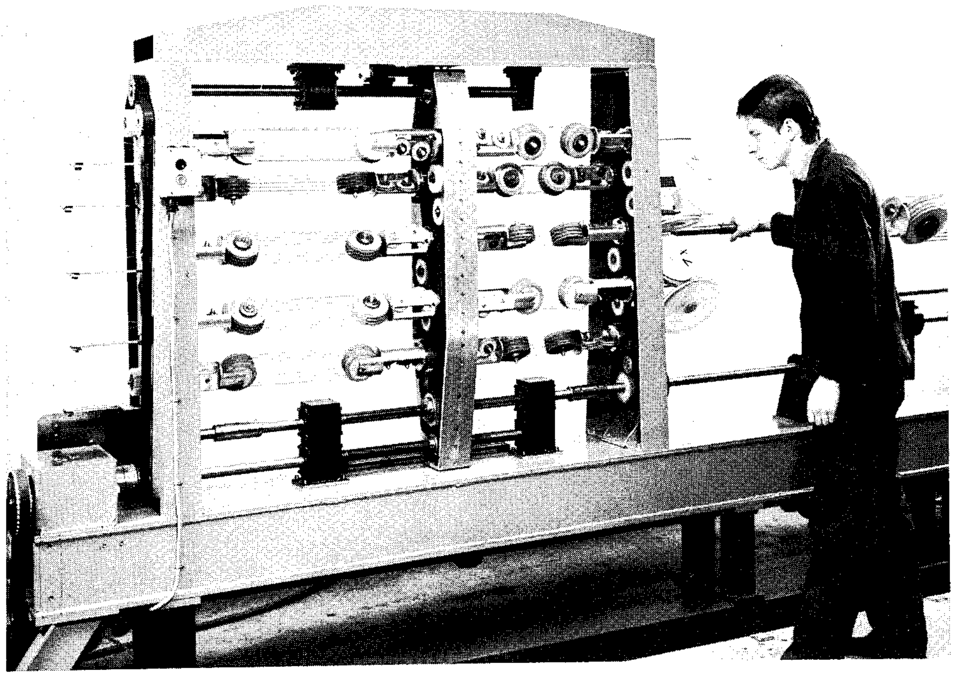

Fig. 14 5-fold star quad twisting equipment as per Fig. 12 for plastic or paper insulated wires having a conductor diameter of 0.4 mm

from left to right via quadding nipples into five double accumulator arrangements. The quadding accumulators rotating in opposite directions - two of which are arranged one after the other - change their capacities inversely thus modulating the pull-off speed at the transition point between two accumulators. Despite the constant rotary movement of the accumulators, the star quads leaving the accumulators on the right-hand side at a constant speed v_o are, in this way, given a periodically alternating direction of lay.

The five accumulators are arranged one on top of the other with a slight lateral displacement and can in case of trouble be serviced from one side.

The horizontally movable middle frame carries out one to and fro movement every 24 seconds at a pull-off speed of 50 m/min so that the direction of lay in the finished quad changes about every 10 meters.

The reversal is effected by two threaded spindles arranged above and below whose rotational speed and direction are changed periodically.

On the right-hand side, the finished quads are led via length-shifting accumulators with constant velocity v_o to the subsequent basic unit stranding equipment. The length-shifting accumulators are discs looped one or several times. They have the effect that the lay reversal points of the individual quads which are subjected to unavoidable geometrical disturbances will be spatially staggered in the finished basic unit so that the influence of quad-to-quad balances will be negligibly small.

The above described quadding equipment was combined with a conventional flier bunching machine for the production of basic units. A trial manufacture where this combined machine operating with 50 m/min pull-off speed was used for the production of PE-insulated local cables

proved successsful. The application of an adhesive at the lay reversal points was not necessary.

The obtained capacitance unbalances are compiled in Table 4 together with the data of conventionally twisted and stranded PE-insulated local cables with 0.4 mm conductor diameter[15].

Not only the capacitance unbalances but also all other electrical and mechanical properties correspond to those of conventionally twisted and stranded cables.

The Basic Unit Stranding Equipment with Breathing Accumulators

Frequently, it is advantageous to produce not only star quads but also the therefrom formed basic units by SZ twisting. In this case, for example, sheathing operations could be added so that it would be possible to produce small-seized cables with plastic sheaths out of single wires in one operation.

A combined quadding and bunching machine with SZ stranding of basic units distinguishes by the requirement of a particularly small amount of machinery.

Such a trial machine for 0.4 mm conductor diameter has been developed and tested successfully. The quadding part corresponds to the already known equipment shown in Fig. 14.

The basic unit stranding part is illustrated in Fig. 15. This, too, is a double accumulator arrangement as shown in Fig. 9. Each accumulator is capable of storing 4 1/2 windings. The direction of lay of the finished basic unit reverses at intervals of about 20 m.

A central spinner provides the finished basic unit with an identification and holding helix before it runs over a stationary pull-off disc to a take-up device not shown in Fig. 15.

The taking-up will be dropped, if the quadding and basic unit stranding equipments are combined with a sheathing line or a main unit stranding machine.

In the test operation, the described double SZ stranding machine for the production of quadded and bunched units has proved to be suitable for PE-insulated as well as paper-insulated cables with 0.4 mm conductor diameter without applying an adhesive. The obtained capacitance unbalances correspond to those compiled in Table 4. Recently, the pull-off speed was increased to 100 m/min. Further investigations have the aim to design an SZ quadding and stranding arrangement for 0.6 mm and 0.8 mm conductor diameter.

kind of capacitance unbalance		SZ twisted star quads			conventionally twisted star quads		
		mean value	max.value	number of measured values	mean value	max.value	number of measured values
		pF/300 m			pF/300 m		
within the quad	k_1	46	274	200	44	300	1850
between different quads within a basic unit	k_9 to k_{12}	13	56	400	13	70	740
between different basic units within a main unit	"	5	22	200	4	18	1600

Table 4:

Capacitance unbalances of polyethylene-insulated local cables with 0.4 mm conductor diameter SZ twisted and conventionally stranded to a basic unit in one single operation.
(For reasons of comparison the data obtained with conventional type of twisting have also been listed.)

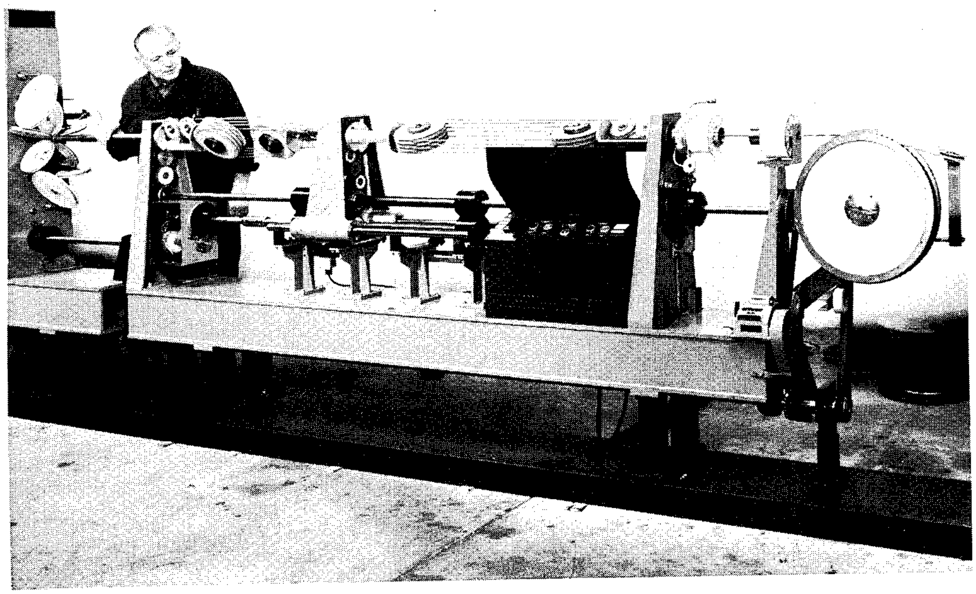

Fig. 15 SZ stranding equipment for producing a basic unit out of star quads fabricated in same operation (refer to Fig. 14)

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MULTI-PAIRED CABLE OF NON LAYER DESIGN FOR LOW CAPACITANCE UNBALANCE TELECOMMUNICATION NETWORKS

by

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Summary

The crosstalk level of symmetrical telephone cables has always been considered as an important factor. Today this is much more pronounced, not only under special conditions in certain trunk cables but also in distribution cables to subscribers and other parts of the network. One reason for this is, that today telephone sets to reasonable costs can be made more efficient by using semiconductive technique as well as more effective material in various components. Also high frequency systems are used to an increasing degree.

As a matter of fact, the effectiveness of a telephone set is today to some extent limited by existing crosstalk level. An improvement means, that longer distances could be spanned and a reduction of conductor size would also be possible, which all opens interesting economical aspects.

The purpose of the idea, presented here, is to reduce the crosstalk by introduction of a new cabling technique, where the pairs or quads not are assembled in concentric layers but repeatedly changing their relative position to each others along the cable length. The excessive build up at couplings between discrete circuits is therefore reduced in a manufacturing method, that uses simplified equipment with low operating costs.

Introduction

It is natural, that the efforts to improve the crosstalk level has been concentrated to the pair or quad in itself. The very first cables were made of concentric layers of single conductors and the introduction of the pair was the first step to reduce the crosstalk. After that followed theories regarding the relation of pitch lengths. Also was proposed, for instance, randomly varied pitch lengths etc. Efforts to further improvements were, and are, concentrated to the achieving of a higher degree of close tolerances of the various components of the pair, such as the copper wire and the insulation.

But very little attention has been paid to the effect the cabling operation may have on the crosstalk properties. From the very first day, the elements, single conductors, pairs, quads, or whatever the components may have been, were assembled to the final cable by placing them in concentric layers around a center element. In each layer the components are running in parallel and adjacent all along the length. Rather late was also introduced the unit, the complete cable consisting of a number of such units, which in themselves are small cables, consisting of a fixed number of elements such as 10, 25, 50 or 100 pairs etc. But this unit is still built up in concentric layers. The method seems to be a copy of the wire rope technique. But, - does it necessarily correspond to the demand of a telephone transmission system?

It is quite natural, that crosstalk between two pairs occurs, when they are in the proximity of each others. It is also evident, that the crosstalk will be higher when they are in the proximity for a long distance. In the conventional layer cabling technique, the pairs are running adjacent, which means as close as possible to each others, and as long as possible, which means all along the total cable length. With this technique, it is evident, that there are also combinations of pairs, which are situated constantly very far away from each others, with very good crosstalk levels. But, in a telephone system, the worst values in general are limiting, and it doesn't help, that some are very good.

As a matter of fact, the cabling system used today can be considered as the less favourable when related to wanted crosstalk properties. Any other, where pairs two and two are more separated, is more corresponding to the transmission demands.

The concentric layer system also introduce systematic irregularity. It is well known, that the mutual capacitance of pairs have different levels in different layers, which also yields for the pairs in the center, giving systematical differencies in the propagation of the signal. Also in this case, the layer technique is the less favourable.

Therefore, besides the efforts to improve the quality of the elements, pairs, quads etc., also the introduction of another cabling technique must be considered as interesting.

The principe of the new cabling technique

According to the crosstalk theory, the capacitance unbalance between two pairs is the dominant factor at least at low frequency. If we look at a conventional cable of ten or twenty pairs like in fig. 1, it is wellknown, that unbalances are occuring only between adjacent pair (also to some extent between center element and the elements in the first layer). Between other combinations the unbalance is negligible. It is also known, that at least the highest unbalances in a cable increases almost with direct proportion to the length.

If we now consider the upper pair in fig. 1, the 10 pair group, and let all other nine pairs repeatedly change the position in relation to this special pair along the cable, then one other arbitrary chosen pair will have an adjacent position only at a fraction of the total cable length. The arbitrary pair can have nine positions in relation to our studied pair, but of these are only two really adjacent and two other positions, in the center, can also be considered as adjacent. Since capacitive coupling only occurs when pairs are adjacent, unbalances are built up on 4/9 of the cable length with corresponding reduction of the unbalances.

As a matter of fact, this principle of reduction of the capacitance unbalances in a cable network installation since long has been used at the splicing operation of the different cable lengths. In that splicing method pairs in one length are chosen at random and spliced to the other length so that two adjacent pairs in one length are not necessarily spliced to adjacent in the next. In that case, the unbalance built up in one cable length will very unlikely be added to a corresponding high value in following length. It can be said, that the method of reduction of high unbalances by random splicing has been substituted by a prefabricated mixing. If random splicing has been considered positive regarding build up of high crosstalk values, then this new method also must be considered as positive. Even to a higher degree, since the mixing is made on very short lengths whereas the build up on whole delivery conventional lengths can be considerable and never will be reduced by the random splicing.

It is evident, that the mixing of the pairs in a bigger group will give even better result. If we study the twenty pair group in fig. 1 we find, that a pair will be adjacent to another arbitrary pair, repeatedly taking different positions in the cable, at a length of 3/19 of the total cable length and corresponding reduction should be waited. However, this calculated reduction, both concerning 10 pairs and 20 pairs groups are just approximately. The tendency is, however, that the mixing of an increasing number of pairs, will reduce the unbalances correspondingly. In a 100 pair unit, for instance, the resulting unbalances would reach just measurable values. On the other hand, a 10-pair group may be considered as the smallest, where this method will give reasonable results. Considering demands of suitable colour coding system and for other practical reasons, the method seems suitable for groups from 10 pairs up to about 30 pairs.

As already mentioned, the cabling operation differs from hitherto used. The pairs, or elements, whatever shape they have, are assembled to a unit, at the present 10 pair groups, with the elements repeatedly changing the relative position to each others. This can be made in different patterns. One of them would be, where the pairs are moved within the group according to a predetermined systematic pattern. This could possibly have the disadvantage, that two pairs will meet each others at fixed intervals, where the crosstalk occurs, and at high frequency transmission this will happen at discrete frequencies, corresponding to the length of the intervals.

Another method, which will be described here, has the mixing points distributed at random distances, which would overcome this disadvantages.

In both cases, the mixing of the pairs also gives a certain flexibility to the unit and could in this respect be compared to the braiding operation of the outer conductor of a flexible coaxial cable.

Production methods

Since we are operating with a fixed unit, in our case a 10 pair group, it is natural, that the twinning of such small number of pairs could be involved in the same operation. Therefore a machine will consist of following parts according to fig. 2:

1. Twinner unit
2. Random impuls generator
3. Mixer
4. Binder head
5. Length measuring device
6. Take up unit

1. Twinning unit

The ten twinning heads are assembled to one unit, fig. 3. Since the forming of a pair in itself is a simple operation, we have tried to make the machine correspondingly simple. This was possible also because the speed was not considered to be necessarily high. As a side effect to this we found, that the machine is operating almost noiseless.

2. The random impuls generator

This device, fig. 4, is giving impulses to the mixing unit and is of an electro-mechanical design.

3. Mixer

In fig. 5 can be seen the system used to form a bunch of ten pairs, where they are positioned in a nonregular way. A pair is entering a die, which can move back and forth in a slot. This movement is achieved by a motor, which starts and stops at pulses from the random impuls device. The other dies are guided by own motors in similar way. All pairs are assembled over two rollers, where they are laying flat in a fanshaped way, formed to a round group in a following die. There is no systematic order between the pairs, and they are repeatedly changing their position on the roller.

4. Binder head

After the assembling die follows a binder, fig. 6, which is defining the pairs in the order they have entered the die. The binder yarn has a suitable colour for identifying purpose.

5. Length measuring device

Fig. 7 shows the length measuring device, which also includes a tachometer, which is syncronizing the drive motors of the different components.

6. Take up

No capstan is used, which means, that the group is fed directly to the take up. Any suitable type can be used, and in fig. 8 is demonstrated a group of four take ups, using one common frame with all driving parts at the top, thus leaving the floor free.

The components in the production unit have a rather simple design. Considering, that a complete 10-pair group is produced from just twenty single conductors, the investment cost is low compared to a conventional way with single twinning machines and a suitable cabling machine. Further, one operator is considered sufficient for more than one group twinner, thus giving also a low production cost.

The final assembling machine, preferably of a drum twister type can also be made rather simple, since it needs equipment for just a few let off devices for the groups and not stands for a big number of single pair reels.

Obtained results

Different tests and deliveries have been made, here will first be referred to one specific project. In this case was ordered 1.640 meter paper insulated cable with conductor size 0,7 mm and totally 1000 pairs. For dimensional reasons it was necessary to divide the pairs in two separate cables with 500 pairs in each. These 500 pairs were built up in 100 pair units, each unit in subunits with 10 pairs each. In this case one cable was made with the 10 pairs in the subunit assembled according to the new system and in the other cable with the pairs in conventional cabling technique; Two pairs in centre and eight in a concentric outer layer.

Both cables were fully coded, even the both conductors in each pair. The cables were delivered in about 200 meter lengths and spliced according to the colour code. In this case adjacent pairs in one length of conventional cable are spliced to adjacent in next etc. The result, when totally 1640 meters were installed can be seen on fig. 9. The cables are, except for the new mixing method, manufactured under identical conditions.

In general, the split up of the cable in small subunits, is favourable also for PCM systems, since crosstalk attenuation level between such groups are at a higher level than within the groups. This makes it easier to find well defined higher levels.

A test production of two polyethylene insulated cables are demonstrated in fig. 10. One cable have mixed 20-pair group, which is compared to a mixed 10-pair. As can be seen, we have got an improvement and is comparable almost to the values obtained between 10-pair groups.

The deviation of the mutual capacitance is also lower for the mixed cable:

	cable conventional	cable mixed
Mutual capacitance nF/km	44	45
Standard deviation Δ^2 C nF	0,61	0,35

The resistance deviation between different pairs are also expected to be less, since cabling losses will be more equal for all pairs.

The diameter of the finished cable is the same and the level of mutual capacitance also about the same in the new cable compared to the conventional.

A selfsupporting polyethylene cable is illustrated in fig. 11.

Conclusion

An improvement of a product can most often be made by spending more money and material, in this case, for instance, by introducing higher precision and more expensive machines as well as shields etc. We have described a new technique, which makes the used machines cheaper to install and also more economical to operate and at the same time by getting an improved product. This

has been achieved by studying the cabling technique from teletransmission demands. We therefore don´t consider this new system as a speciality, adoptable for one or another manufacturer, but, in general, as a more natural way of building up a telephone cable for general purpose.

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Since 1968 at L M Ericsson in the Telephone Cables Division, Stockholm.

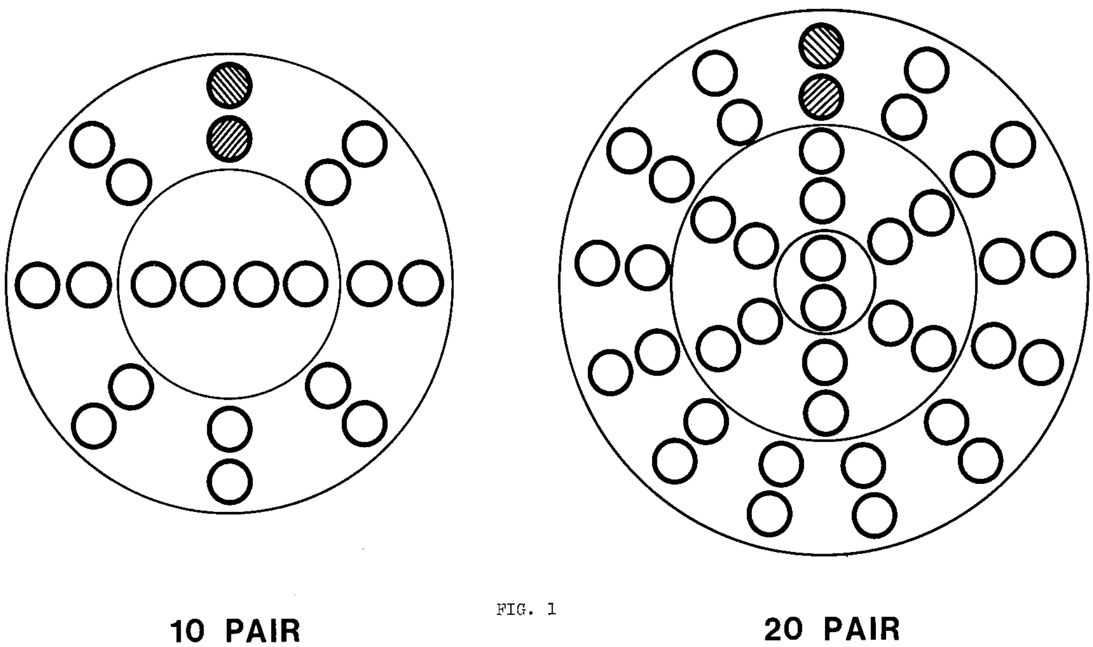

FIG. 1

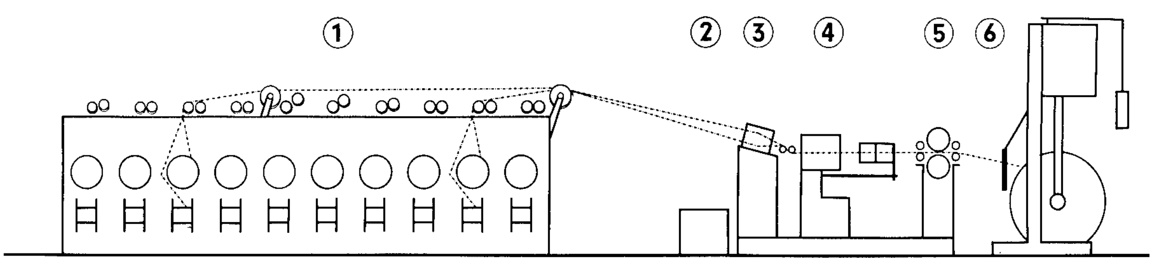

FIG. 2

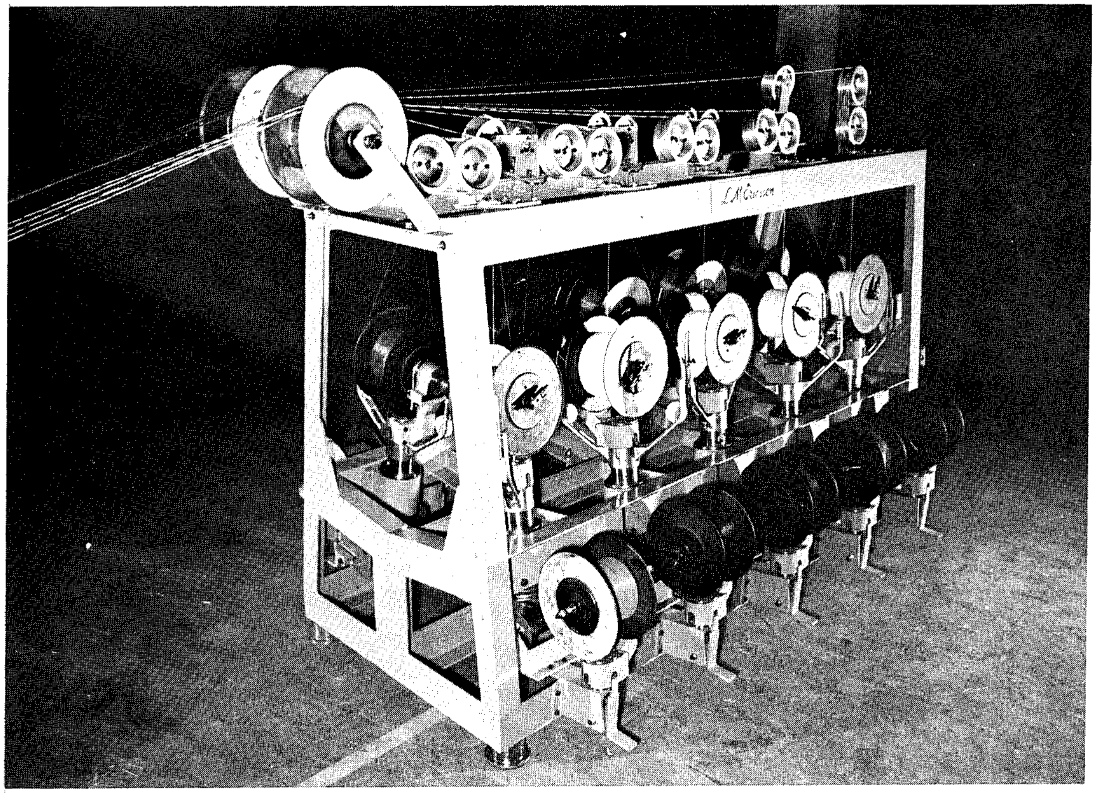

FIG. 3

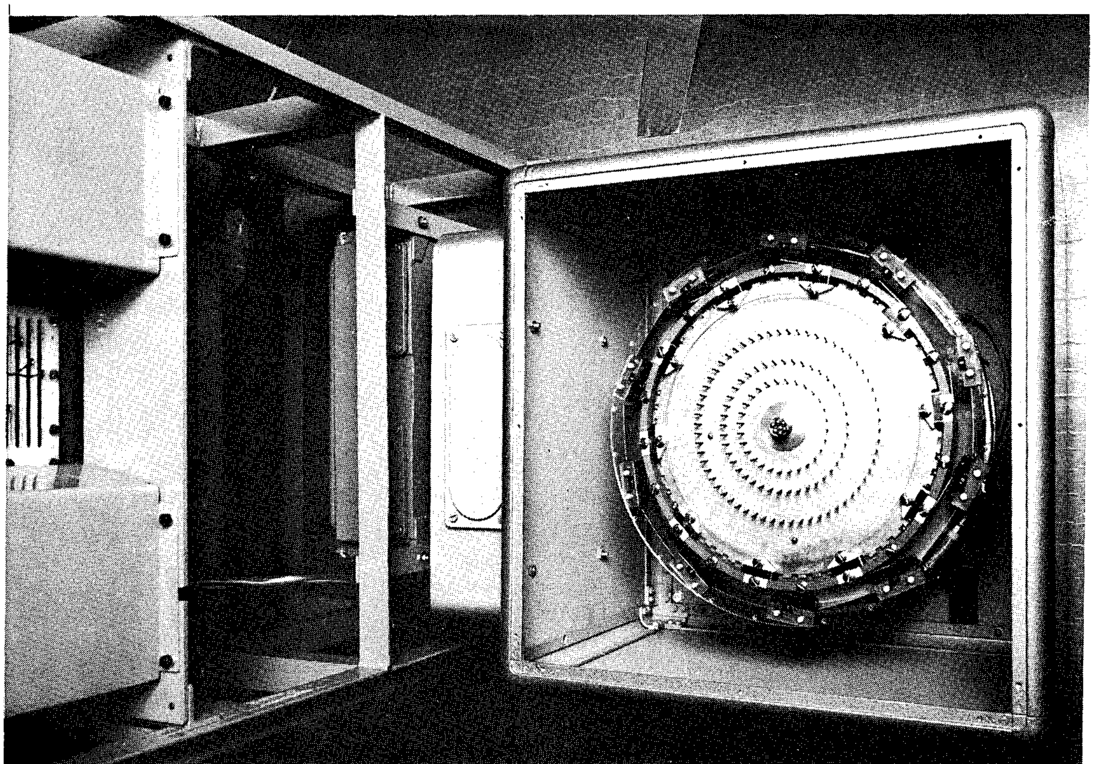

FIG. 4

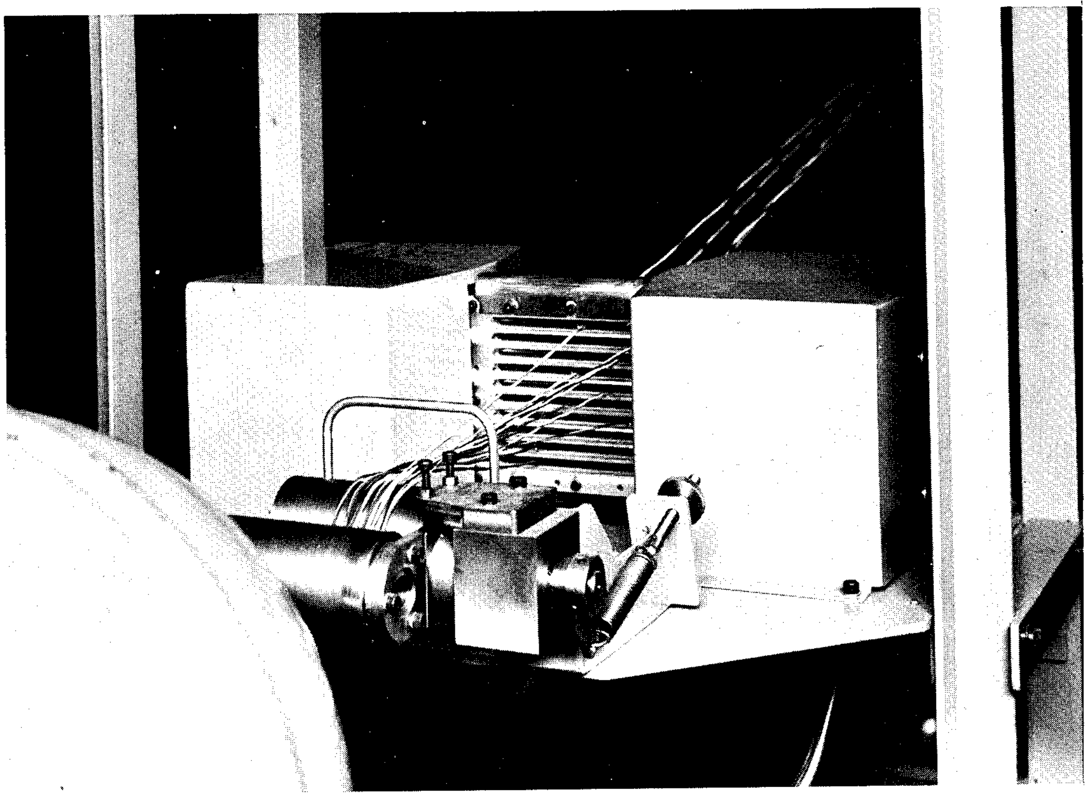

FIG. 5

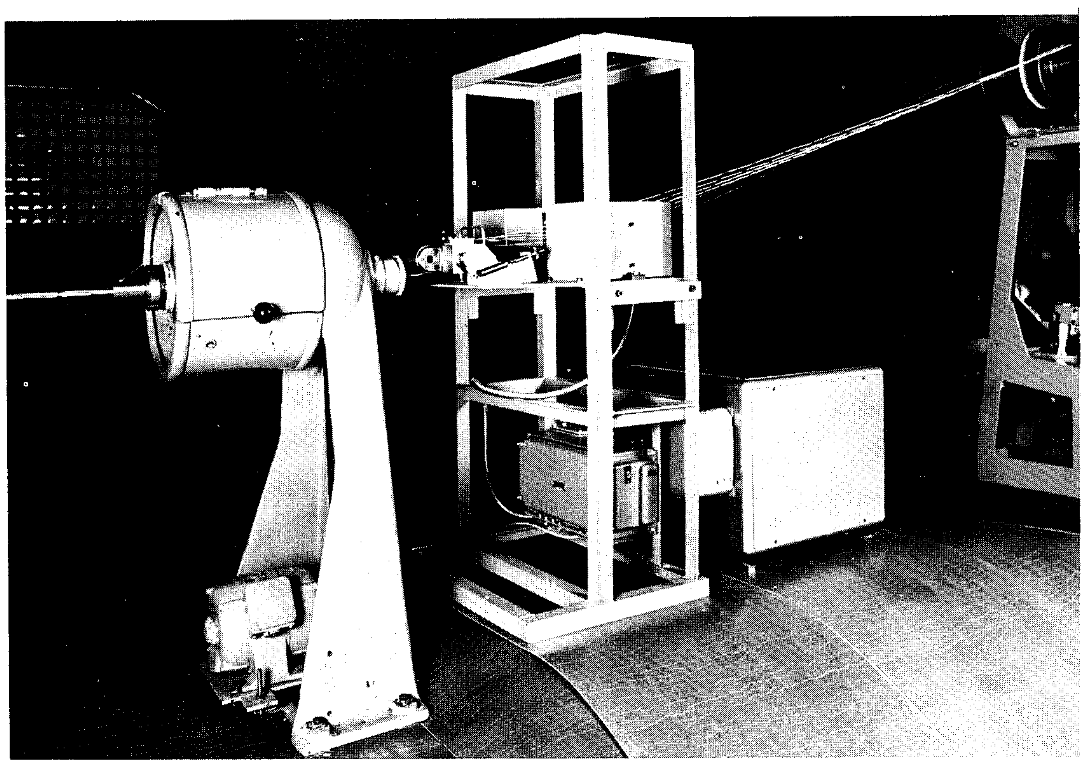

FIG. 6

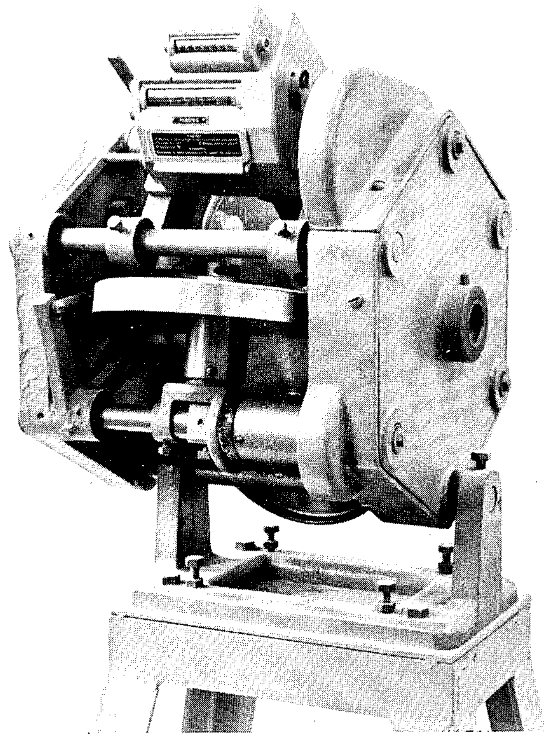

FIG. 7

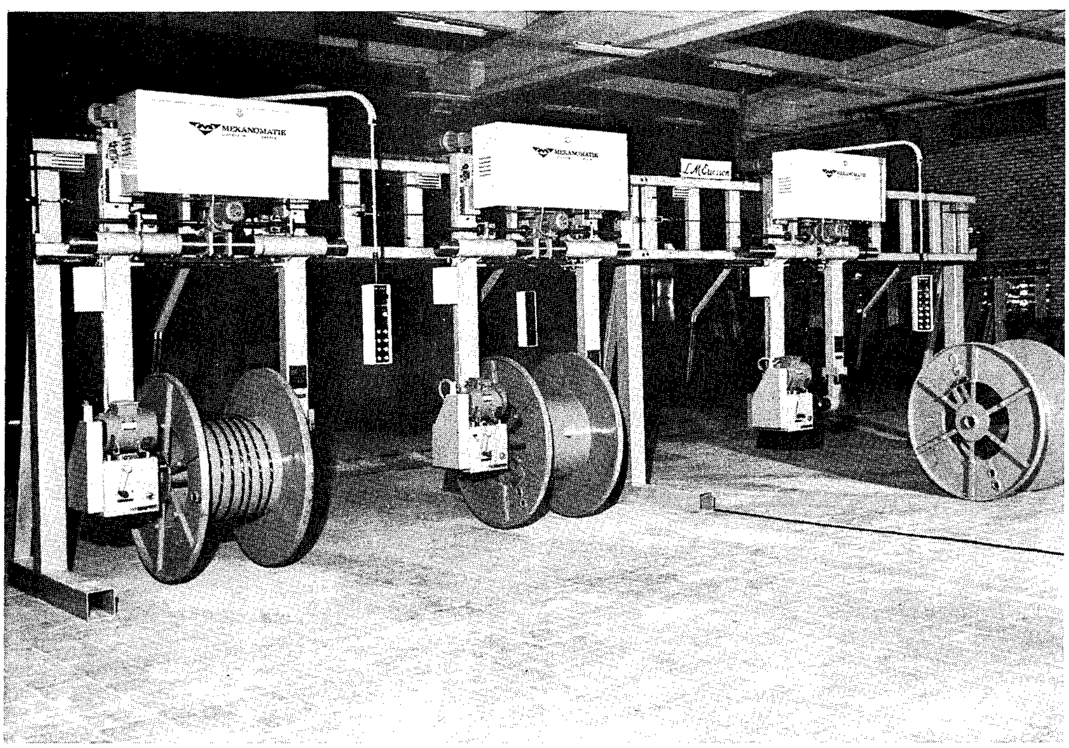

FIG. 8

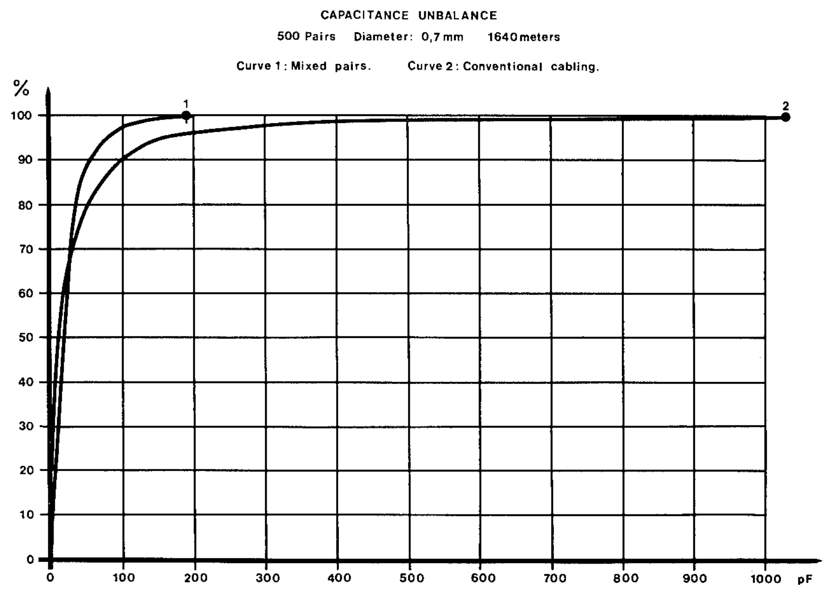

FIG. 9

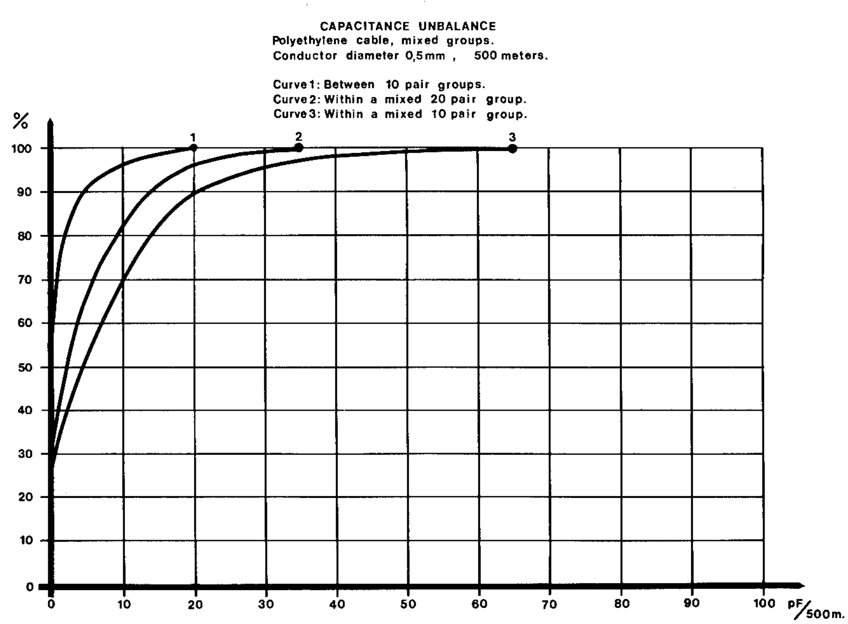

FIG. 10

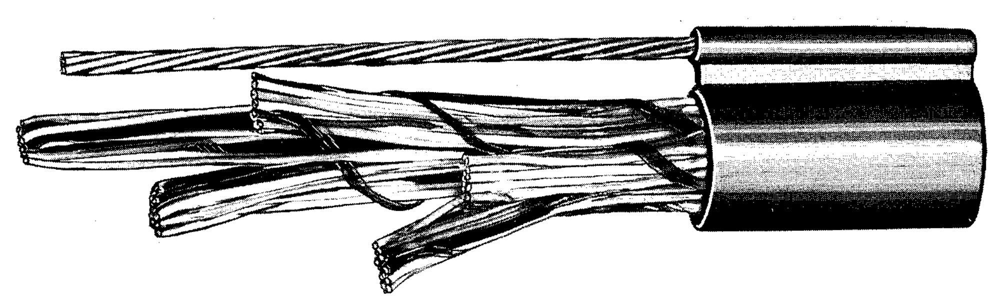

FIG. 11

NEW TYPE PAIRED CABLE FOR HIGH SPEED PCM TRANSMISSION

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Abstract

This paper describes new type paired cable for high speed PCM transmission. Design philosophy, design methods, transmission properties of the paired cable, attained PCM transmission speed and the results of experiments on a 100 Mb/s PCM transmission system are given.

Introduction

In Japan, the PCM-24 system was first put to commercial use in 1965. Ever since, it has been widely adopted to furnish economical voice channels for short haul trunks. In 1968, the PCM-120 (PCM-8Mb/s) system was developed. Concerning PCM transmission speed, however, it seems that there is a great gap of suitable transmission medium between existing balanced cable and coaxial cable. Suitable clock frequency for existing balanced cable is considered to be about 10 MHz and for coaxial cable to be several hundreds of MHz[1].

In order to fill the gap, E. C. L. proposed[2] and researched PEF insulated paired cable with shielded units. Success in realizing this new cable, whose clock frequency is 100 MHz, predicts wider PCM system feasibility. This cable can transmit two way signals in one cable, because the near-end crosstalk coupling loss between West to East circuits and East to West circuits is made negligible by unit shielding. Paired cable is used instead of star quad cable in order to avoid poor crosstalk characteristics within the quad.

Design Philosophy

1. Cable Diameter

When designing a new paired cable, it is necessary to research suitable cable structure, suitable conductor diameter and suitable impedance or capacitance. Transmission line cost is considered to be one measure to solve these problems, so cost was set as a standard. Though able to use two cables or a unit shielded cable in order to reduce near-end crosstalk, unit shielded cable was developed, because it is convenient to utilize existing 75 mm inner diameter conduit.

Cable material cost C_M /km can be expressed as follows:

$$C_M = n_u \left[A n_{up} r_i^2 + B\left(\frac{k^2}{4} - 1\right) n_{up} r_i^2 + Ck\sqrt{n_{up}}\, r_i + D \right] + E \tag{1}$$

n_u : unit numbers in a cable
n_{up} : pair numbers in a unit
r_i : conductor radius (mm)
$2r_a$: wire diameter (mm)
k : $k = 2r_a/r_i$

A, B, C, : proportional coefficient of each term
D, E : constant term

In Equation (1) the first term in the bracket is the material cost of conductors, the second term is the cost of conductor insulation material, the third and the fourth term are the cost of tapes, for instance polyethylene tape, unit shielding tape and so on.

E is the cost of cable sheath material. In Equation (1) it is assumed that the ratio of the total wire area to the inner area of a unit is 1/2. This assumption gives a good approximation due to past experience. Accordingly, if we put r_{ua} (mm) as a unit radius the next equation becomes

$$n_{up} r_i^2 = \frac{r_{ua}^2}{k^2} \tag{2}$$

From Equations (1) and (2), equation (3) is given.

$$C_M = n_u \left[A\frac{r_{ua}^2}{k^2} + B\left(\frac{k^2}{4} - 1\right)\frac{r_{ua}^2}{k^2} + Cr_{ua} + D \right] + E \tag{3}$$

Equation (3) shows that, if we set cable diameter, cable sheath, unit numbers contained in a cable, taping under and upper unit and k, the C_M is independent of conductor radius and pair numbers n_{up} in a unit.

Cable cost may be expressed as αC_M, where α is the function of cable structure. The cost of conduit and the cost of construction, for instance, conduit construction is set as F, then F is nearly independent of cable diameter, therefore allover cable cost K is expressed as follows:

$$K = \alpha C_M + F \quad (\text{per km}) \tag{4}$$

where K is almost independent of n_{up} or r_i.

Consequently, overall cost of one pair in the cable, C_1, becomes

$$C_1 = \frac{1}{n_u n_{up}} K$$

$$= \alpha \left[A r_i^2 + B\left(\frac{k^2}{4} - 1\right) r_i^2 + C \frac{k}{\sqrt{n_{up}}} r_i + \frac{D}{n_{up}} \right] + \frac{\alpha E + F}{n_u n_{up}} \tag{5}$$

Equation (5) means that, when k and r_i are fixed, C_1 becomes cheaper when the number of pairs contained in a cable is increased, or in other words, when cable diameter is made larger. However, cable diameter is limited by the inner diameter of installed conduit. Therefore, the outer diameter of the new cable is limited to about 71.5 mm in order to use existing installed conduit whose inner diameter is 75 mm.

2. Selection of Conductor Radius

Here, also an economical standard of selecting suitable conductor radius is used. Transmission line cost is determined by overall cable cost and repeater cost. Transmission line cost C_{1t} per one pair at clock frequency f_M (MHz) is given by the following equation.

$$C_{1t} = \frac{K}{n_u n_{up}} + \frac{R f_M^{x+\frac{1}{2}}}{G} \frac{a k}{r_{ua}} \sqrt{n_{up}} + \frac{Rb}{G} f_M^{x+1} \quad (\text{per km}) \tag{6}$$

K : same as Equation (4)

n_{up}, n_u, r_{ua}, r_i : same as Equation (1)

a, b: constants of cable loss
cable loss = $(a\sqrt{f_M}/r_i) + b f_M$ (dB/km)

$R f_M^x$: cost of a repeater at clock frequency f_M (MHz)

G : Equalizer gain (dB) at clock frequency f_M (MHz)

From Equation (6) it is concluded that C_{1t} becomes cheapest when the following relation is satisfied.

$$n_{up\,(opt)} = \left[\frac{2G(K/n_u) r_{ua}}{R f_M^x a \sqrt{f_M}\, k} \right]^{2/3} \tag{7}$$

or from Equation (7) and (2)

$$r_{i\,(opt)} = \left[\frac{R f_M^x a \sqrt{f_M}}{2G(K/n_u)} \right]^{1/3} \left(\frac{r_{ua}}{k}\right)^{2/3} \tag{8}$$

Equation (8) means, for instance, the higher the repeator cost the larger the conductor diameter r_i. But the already presented discussion is only correct within the following equations restriction.

$$\ell_x > \frac{G}{(a/r_i)\sqrt{f_M} + b f_M} \tag{9}$$

Where ℓ_x (Km) is the longest repeator spacing determined by crosstalk coupling loss.

Fig. (1) shows the numerical result of optimum conductor radius r_i about a unit shielded cable, when a repeater cost changed, where k is chosen as 5.4, G is 90 dB and f_M is 100 MHz.

3. Transmission speed limitation for paired cable

Transmission speed limitation for paired cable is considered from an economical standpoint. In order to neglect near-end crosstalk, a unit shielded cable was adopted.

For this case, the transmission speed limitation arises from cable loss increase and far-end crosstalk coupling loss degradation. By using already used notations, one pair system cost per 1 MHz, C_{1a}, (per km) is expressed as follows:

$$C_{1a} = \frac{K}{n_u n_{up}} \frac{1}{f_M} + \frac{1}{G} \frac{a}{r_i} R f_M^{x-1} \quad (\text{per km}) \tag{10}$$

where cable leakage loss is neglected.

From Equation (10), it is concluded that, when $x < 0.5$, transmission speed limitation does not occure due to cable loss. The faster the speed. the lower the system cost.

For the case of $x > 0.5$, transmission speed limitation arises from cable loss, and the limited clock frequency f_{Ma} is given by the following equation:

$$f_{Ma} = \left[\frac{K G k^2}{R a \left(x - \frac{1}{2}\right) n_u r_{ua}^2} \right]^{\frac{2}{2x+1}} r_i^{\frac{6}{2x+1}} \tag{11}$$

The larger the conductor radius, the higher the limited clock frequency f_{Ma}.

Next we examine transmission speed limitation arising from far-end crosstalk. Consider the case where clock frequency is f_0 (MHz) and admissible longest repeator spacing is l_0 (km). If we have a higher clock frequency f_M (MHz) of more than f_0 (MHz), the repeator spacing becomes ℓ_M (km), shorter than ℓ_0 (km). These distances and frequencies result in the next relation.

$$\left(\frac{\ell_M}{\ell_0}\right) = \left(\frac{f_M}{f_0}\right)^{-2} \tag{12}$$

Where it is assumed that signal to far-end crosstalk power ratio (dB) decreases with 10 logℓ. Under the restriction of Equation (12), one pair system cost per 1 MHz, C_{1x}, is given by the following equation:

$$C_{1x} = \frac{K}{n_u\, n_{up}}\,\frac{1}{f_M} + \frac{1}{\ell_0\, f_0^2}\, R\, f_M^{x+1} \tag{13}$$

From Equation (13), the limited clock frequency f_{MX} (MHz) is obtained as follows:

$$f_{MX} = \left[\frac{K k^2 \ell_0\, f_0^2}{n_u\, r_{ua}^2\,(x+1)\,R}\right]^{\frac{1}{x+2}} r_i^{\frac{2}{x+2}} \text{ (MHz)} \tag{14}$$

Equation (14) means that, whatever the value of x, there is always a limited clock frequency f_{MX} (MHz) caused by far-end crosstalk. Therefore, the deduction of system cost by using paired cable largely depends upon improvement of far-end crosstalk coupling loss. Fig. 2 shows that relative system cost variation per 1 km· 1 MHz versus clock frequency f_M (MHz). Curve ① shows the case when limiting clock frequency is 100 MHz and curve ② shows the limiting frequency is 200 MHz, where x is chosen as 0.7.

4. Selection of the Value of k

Here we examine the optimum k. In other word we examine the optimum characteristic impedance or capacitance of a pair. In the foregoing section we discussed about optimum pair number n_{up} or conductor radius r_i, when k is fixed. Therefore, here only the effect of k on system cost is examined under the condition of pair number n_{up} or wire diameter 2 r_a being fixed. There are two standards used to select optimum k value: one is a purely economical standpoint, the other is the engineering standpoint.

Fig. 3 shows one example of system cost against k, where an effective dielective constant ratio of 1.6 is used.

From Fig. 3, the value of k of from 5.0 to 6.0 seems to be suitable. However it's value is affected by repeator cost.

Therefore it is necessary to study, more rigorously the optimum value of k from an engineering standpoint.

5. Comparison with Coaxial Pair

Comparison with coaxial pair is an important problem when designing new type cable. Here, we compare the necessary copper quantity required to realize the same cable loss. Conditions of comparison are as follows: One is on the basis of loss minimum where design of loss minimum means that the design to make cable loss minimum when an insulated wire diameter is fixed or coaxial outer conductor's inner radius is fixed. Two is both PEF insulation with an effective dielectric constant ratio of 1.6. Generally in the high frequency domain, cable loss is expressed as follows:

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \qquad \text{(nep/km)} \tag{15}$$

Neglecting leakage loss compared with conductor loss, α nearly equals $\frac{R}{2}\sqrt{\frac{C}{L}} \doteqdot \frac{R}{2}\frac{1}{Z_c}$, where Zc is characteristic impedance. As will be mentioned later, the optimum charactieristic impedance, for a small pair number shielding cable (for instance 7 pairs shielded), is about 145Ω (at 1 MHz) and that of a coaxial pair is about 64Ω (at 1 MHz). Therefore, using Rc as the notation of resistance R of coaxial pair and R_p as that of paired cable the following relation between Rc and R_p realizes the same cable loss for both cable: Rc = 0.44 R_p.

Therefore it is deducted that the copper quantity necessary for a coaxial pair is much more than that required for a shielded pair, when both cable loss are the same. Fig. 4 shows the ratio of copper quantity of a coaxial pair to copper quantity of a shielded pair, when both cable losses are the same. It shows that the larger the cable loss, the larger the ratio.

This is one of the reasons why shielded pair cable was adopted for high speed PCM transmission.

Design Methods

1. Determination of Optimum k

The problem in determining optimum k is how to select conductor radius in order to keep cable loss minimum when an insulated diameter 2 r_a is constant.

Fig. 5 shows the concept. In order to determine the optimum k, the primary constants of a shielded pair type cable are studied. The following equations are used.

$$R = 2\left(R_i + R_n + R_h + R_e \right)^{3,4} \qquad (\Omega/\mathrm{m})$$

$$L = 2\left(L_i + L_n + L_h + L_e + L_a \right)^{3,4} \qquad (\mathrm{H/m})$$

$$C = \frac{\pi \epsilon_o \epsilon_r}{\ln\left(\frac{2r_a}{r_i}\right) - \frac{\left(\frac{2r_a}{R_1}\right)^2}{2\left\{1-\left(\frac{r_e}{R_1}\right)^2\right\}^2} - \left(\frac{r_i}{2r_a}\right)^2 \left[1 - \frac{\left(\frac{2r_a}{R_1}\right)^2}{\left\{1-\left(\frac{r_e}{R_1}\right)^2\right\}^2}\right]^2 - \Sigma F_e} \qquad (\mathrm{F/m})$$

$$G = \omega C \tan\delta \qquad (\mho/\mathrm{m}) \tag{16}$$

R is resistance, L is inductance, C is capacitance G is conductance of a pair,

Where

$$R_i = \frac{1}{\pi r_i^2 \sigma_i} f_i^{(R)}$$

$$L_i = \frac{\mu_i}{2\pi} f_i^{(L)}$$

$$R_n = \frac{1}{\pi r_i^2 \sigma_i} F_n f_n^{(R)}$$

$$L_n = (-)\frac{\mu_i}{2\pi} F_n \cdot f_n^{(L)}$$

$$R_h = \frac{2 r_a^2}{\pi \sigma_h \delta_h^2 R_1^2} \sum_{n=1,2,\cdots}^{\infty} n V_n \left(\frac{r_e}{R_1}\right)^{2(n-1)}$$

$$L_h = (-)\frac{\mu_0 r_a^2}{\pi R_1^2} \sum_{n=1,2,\cdots}^{\infty} n U_n \left(\frac{r_e}{R_1}\right)^{2(n-1)}$$

$$R_e = \Sigma \frac{1}{\pi r_i^2 \sigma_i} F_e f_n^{(R)}$$

$$L_e = (-)\Sigma \frac{\mu_i}{2\pi} F_e f_n^{(L)}$$

$$L_a = \frac{\mu_0}{2\pi} \ln \frac{2r_a}{r_i}$$

Where

$$f_i^{(R)} = \text{Real part of } \frac{(1+j)}{2\delta_i} r_i \frac{J_0\left(\frac{1+j}{\delta_i} r_i\right)}{J_1\left(\frac{1+j}{\delta_i} r_i\right)}$$

$$f_i^{(L)} = \text{Real part of } \frac{\delta_i}{(1+j) r_i} \frac{J_0\left(\frac{1+j}{\delta_i} r_i\right)}{J_1\left(\frac{1+j}{\delta_i} r_i\right)}$$

$$f_n^{(R)} = \text{Real part of } \frac{(1+j)}{\delta_i} r_i \frac{J_1\left(\frac{1+j}{\delta_i} r_i\right)}{J_0\left(\frac{1+j}{\delta_i} r_i\right)}$$

$$f_n^{(L)} = \text{Real part of } (-) \frac{J_2\left(\frac{1+j}{\delta_i} r_i\right)}{J_0\left(\frac{1+j}{\delta_i} r_i\right)}$$

$$F_n = \left(\frac{r_i}{2r_a}\right)^2 \left[\left\{ 1 - \left(\frac{2r_a}{R_1}\right)^2 \sum_{n=1,2,\cdots}^{\infty} n \left(\frac{r_e}{R_1}\right)^{2(n-1)} U_n \right\}^2 + \left\{ \left(\frac{2r_a}{R_1}\right)^2 \sum_{n=1,2,\cdots}^{\infty} n \left(\frac{r_e}{R_1}\right)^{2(n-1)} V_n \right\}^2 \right]$$

$$V_n = \frac{R_1}{4n\delta_h}\left[\sinh\frac{2d}{\delta_h} + \sin\frac{2d}{\delta_h}\right] |S_n|^2$$

$$U_n = \frac{R_1}{4n\delta_h}\left[\sinh\frac{2d}{\delta_h} - \sin\frac{2d}{\delta_h} + \frac{R_1}{n\delta_h}\left(\cosh\frac{2d}{\delta_h} - \cos\frac{2d}{\delta_h}\right)\right] |S_n|^2$$

$$\frac{1}{|S_n|^2} = \frac{1}{2}\left(\cosh\frac{d}{\delta_h} + \cos\frac{2d}{\delta_h}\right) + \frac{R_1}{2n\delta_h}\left(\sinh\frac{2d}{\delta_h} - \sin\frac{2d}{\delta_h}\right) + \left(\frac{R_1}{2n\delta_h}\right)^2 \left(\cosh\frac{2d}{\delta_h} - \cos\frac{2d}{\delta_h}\right)$$

$$F_e = r_i^2 (2r_a)^2 \left[\frac{\left[1+\left(\frac{r_a}{r_p}\right)^2\right]}{r_p^4\left[1-\left(\frac{r_a}{r_p}\right)^2\right]^3} + \frac{\left[\left(1-\left(\frac{r_e}{R_1}\right)^2\right)\left(1-\left(\frac{r_e'}{R_1}\right)^2\right)+\left(\frac{r_p}{R_1}\right)^2+\frac{r_e^2 r_a^2}{R_1^4}\right]}{R_1^4\left[\left(1-\left(\frac{r_e}{R_1}\right)^2\right)\left(1-\left(\frac{r_e'}{R_1}\right)^2+\left(\frac{r_p}{R_1}\right)^2-\frac{r_e^2 r_a^2}{R_1^4}\right]^3} \right]$$

and where

r_i	:	conductor radius	(m)
σ_i	:	conductivity of conductor	($\mho$/m)
σ_h	:	conductivity of shielding material	($\mho$/m)
σ_i	:	skin depth of conductor	(m)
δ_h	:	skin depth of shielding material	(m)
μ_0	:	free space permeability	(H/m)
μ_i	:	permeability of conductor	(H/m)
$2r_a$	:	an insulated wire diameter	(m)
r_e, r_e'	:	eccentric distance of pairs	(m)
R_1	:	shielding material radius	(m)
r_p	:	distance between pairs	(m)
d	:	thickness of shielding material	(m)
$\tan\delta$	=	4×10^{-4}	

J_0, J_1, J_2 are Bessel's function of zero, first and second order, and, in Equation (16), Σ means the sum of the effect of the surraundings pairs for a pair under consideration.

$\omega = 2\pi f$, f : frequency (Hz)
ϵ_o : free space permittivity (F/m)
ϵ_r : effective dielectric constant ratio

Fig. 6 shows these distance relations.

In a high frequency region, attenuation constant can be expressed as follows:

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} = \alpha_R + \alpha_G \quad (\mathrm{nep/km})$$

where α_R is conductor loss and α_G is leakage loss and α_G is nearly equal to $(\omega/2)\tan\delta\sqrt{\mu_0\epsilon_0\epsilon_r}$. α_R can be expressed as the following equation from Equation (16)

$$\alpha_R = \frac{1}{2(2r_a)\,\delta_i\,\sigma_i}\sqrt{\frac{\epsilon_0\epsilon_r}{\mu_0}}\,\cdot$$

$$f_\alpha\left(\frac{2r_a}{r_i},\ \frac{r_a}{R_1},\ \frac{r_e}{R_1},\ \frac{r_a}{r_p},\ \frac{r_p}{R_1},\ \frac{r_e'}{R_1},\ \sqrt{\frac{\sigma_i}{\sigma_h}}\right) \tag{17}$$

f_α is a function of each parameter in the parentheses. From Equation (17), optimum $k, 2r_a/r_i$, is obtained by solving the following equations simultaneously.

$$\frac{\partial\alpha_R}{\partial(2r_a/r_i)} = 0\ ,\ \frac{\partial\alpha_R}{\partial t_{PE}} = 0 \tag{18}$$

The numerical results are shown in Fig. 7.

From Fig. 7, it is realized that there is a broad band of k where cable loss does not change much. Here, we determine that the point of 0.5 % loss increase from the lowest cable loss at 100 MHz is optimum. Then we are able to obtain the optimum k and optimum characteristic impedance for each number of shielded pairs, as shown in Table 1.

Optimum characteristic impedance z_c and k

Table 1

Number of shielded pairs	k	z_c (at 100 MHz)
3 pairs	5.4	135
4 pairs	5.4	137
5 pairs	5.4	138
7 pairs	5.4	139
19 pairs	5.7	156
37 pairs	5.8	160

(for the first layer pair)
$\epsilon = 1.6$

2. Error Probabilities versus Signal to Gaussian Noise Ratio

Error probabilities versus signal to gaussian noise ratio for a bipolar pulse train has already been analyzed. [5, 6] In this analysis, amplitude distribution of intersymbol interference, amplitude distribution of thermal noise and noises of equalizer, and amplitude distribution of crosstalk noises are considered simultaneously at a pulse detecting point. Using the results of this analysis, error probabilities versus signal to gaussian noise ratio for equalized pulses of rational function, shown in Table 2, can be numerically obtained. The numerical results are shown in Fig. 8.

Equalized pulses of rational function used in calculating error probability

Table 2

equalized pulse form number	high frequency cutoff		low frequency cutoff	
	f_H/f_0	n	f_L/f_0	m
①	1.452	15	3×10^{-3}	3
②	1.518	20	"	"
③	1.695	20	"	"
④	1.702	25	"	"
⑤	1.905	25	"	"

f_0 : clock frequency (MHz)
f_H/f_0: normalized high cutoff frequency
n : order of high frequency cutoff of rational function
f_L/f_0: normalized low cutoff frequency
m : order of low frequency cutoff of rational function

In Fig. 8, r_0 shows equalized pulse amplitude, σ_G^2 is the expected value of total noise power at the pulse detecting point.

3. Necessary Signal to Multiple Far-End Crosstalk Power Ratio

When considering only far-end crosstalk noise, thermal noise and noises of the equalizer, σ_G^2 is given by

$$\sigma_G^2 = \sigma_F^2 + \sigma_B^2 \tag{19}$$

where σ_F^2 is the expected value of far-end crosstalk power at pulse detecting point and σ_B^2 is expected value of thermal noise power and noises of equalizer at the pulse detecting point. In calculation of Fig. 8 it is assumed that the probability density function of far-end crosstalk instantaneous amplitude y_F and that of thermal noise and noises of equalizer instantaneous amplitude y_B at the pulse detecting point are, respectively,

$$P_F(y_F) = \frac{1}{\sqrt{2\pi}\ \sigma_F}\ e^{-\frac{1}{2\sigma_F^2} y_F^2} \qquad (20)$$

$$P_B(y_B) = \frac{1}{\sqrt{2\pi}\ \sigma_B}\ e^{-\frac{1}{2\sigma_B^2} y_B^2} \qquad (21)$$

Necessary mean value of signal to multiple far-end crosstalk power ratio Xem(db) at clock frequency f_0 for a pulse equalizing section, in order to realize an error rate under E, is obtained from Equation (19), as follows:

$$X_{em} > \left[20 \log \frac{\gamma_0}{\sigma_G}\right]_E + 20 \log \frac{\sigma_{F0}}{\gamma_0} - 10 \log \left[1 - \left(\frac{\sigma_B}{\sigma_G}\right)^2\right] \qquad (22)$$

where $\left[20 \log \frac{\gamma_0}{\sigma_G}\right]_E$ is signal to gaussian noise ratio giving error rate E, which is given by Fig. 8. σ_{F0} is as follows:

$$\sigma_{F0}^2 = \frac{1}{2\pi}\int_0^\infty \Psi(w)\ |W(w)|^2 \left(\frac{w}{w_0}\right)^2 dw \quad \text{(Watt)} \qquad (23)$$

where $\Psi(w)$ is transmitting power spectrum of the pulse train, $W(w)$ is overall transfer function of one pulse equalizing section. If we take the error rate of one pulse equalizing section as 10^{-10}, signal to gaussian noise ratios of each equalizing pulse can be determined from Fig. (8). But we add this signal to gaussian noise ratio plus 8 dB, considering signal to gaussian noise ratio degradation based on deviation of automatic gain control, variation of transmitting pulse amplitude, jitter and timing pulse width and degradation of repeater performance with the passage of time.

Then the necessary Xem per one pulse equalizing section is obtained by calculating Equation (22). Results are shown in Fig. 9. Though, in Fig. 9, the curves of equalized pulse form number are shown only about ① and ⑤ , the other equalized pulse number's curves are between these values. From Fig. 9, it is concluded that the necessary mean value of signal to multiple far-end crosstalk power ratio Xem for one equalizing section is 18 db at 100 MHz and the gain of equalizer at clock frequency is limited to about 90 dB, concerning the equalized wave forms shown in Table 2. It is necessary, however, to study the added 8 dB more exactly.

4. Errorrate and Admissible Standard Deviation of Far-End Crosstalk Coupling Loss

In the analysis of error rate in a signal to gaussian noise ratio, it is assummed that the probability density function $P_F(y_F)$ of far-end crosstalk instantaneous amplitude y_F at the detecting point is normal distribution. That is shown in Equation (20). From Equation (20), the probability density of $|y_F|^2$, $P_{\sigma_F^2}(x)$ is found to be

$$P_{\sigma_F^2}(x) = \frac{1}{\sqrt{2\pi x}\ \sigma_F}\ e^{-\frac{1}{2\sigma_F^2}} \qquad (24)$$

σ_F^2 (Watt) at the detecting point is expressed as follows:

$$\sigma_F^2 = \frac{1}{2\pi}\int_0^\infty \Psi(w)\ |W(w)|^2 k_x (\ell/\ell_0)^q \left(\frac{w}{w_0}\right)^2 dw \qquad (25)$$

Integrating Equation (23) leads to

$$\sigma_F^2 = k_x\ (\ell/\ell_0)^q\ \sigma_{F0}^2 \qquad (26)$$

where ℓ is the cable length and k_x is signal to far-end crosstalk ratio (Watt) at frequency f_0 and cable length ℓ_0, and q is a constant which will be mentioned later.

The probability density of k_x, $P_k(x)$, can be expressed as follows:

$$P_k(x) = \frac{\lambda^\nu}{\Gamma(\nu)}\ x^{\nu-1} e^{-\lambda x} \quad (\nu > 0,\ \lambda \geq 0) \qquad (27)$$

Then $P_{\sigma_F^2}(x)$ leads to the next equation:

$$P_{\sigma_F^2}(x) = \frac{\lambda^\nu}{\Gamma(\nu)}\int_0^\infty \frac{1}{\sqrt{2\pi(\ell/\ell_0)^q u\ \sigma_{F0}^2}}\ u^{\nu-1} e^{-(\lambda u + \frac{x}{2u(\ell/\ell_0)^q \sigma_{F0}^2})} du \qquad (28)$$

The average loss in db of σ_F^2 is given by $-10 \log \sigma_F^2$, and, from Equation (28), we have the average loss

$$-10 \log \sigma_F^2 = -(10 \log e)\left[\Psi(\nu) + \Psi(1/2)\right] + 10 \log \lambda - 10 \log 2\sigma_{F0}^2 - 10\,q \log \frac{\ell}{\ell_0}$$

and the standard deviation in db

$$\sigma_t = (10 \log e)\left[\Psi'(\nu) + \Psi'\left(\tfrac{1}{2}\right)\right]^{1/2} \qquad (29)$$

In Equation (27), if we put $\nu = \frac{1}{2}$, $\lambda = \frac{1}{2\sigma_{kx}^2}$, $P_k(x)$ leads to the next equation:

$$P_k(x) = \frac{1}{\sqrt{2\pi x}\ \sigma_{kx}}\ e^{-\frac{1}{2\sigma_{kx}^2}} \qquad (30)$$

Equation (30) is obtained if we assumed that the induced currents of the disturbed pairs are normally distributed with an average of zero. This correspounds to Equation (24). The mean loss in db of k_x and the standard deviation in db are obtained as follows:

$$-10\log k_x = -10\log\nu + 10\log\lambda$$

$$\sigma_{kx} = (10\log e)\,[\Psi'(\nu)]^{1/2} \qquad (31)$$

in which $\Psi(x)$ is the derivative of the logarithm of the gamma function. If we put $\nu=\frac{1}{2}$ in Equations (29) and (31), σ_t and σ_{kx} are obtained, respectively, as 13.64 db and 9.65 db.

From the above discussion, it is concluded that the assumption (20) corresponds to the induced currents of the disturbed pairs being normally distributed with average zero at an arbitrary frequency and that far-end crosstalk coupling loss standard deviation in db is 9.65 db. This 9.65 db corresponds to 13.64 db, which is the standard deviation of σ_F^2 in time domain.

Therefore, in order to attain an error rate of 10^{-10} in an equalized section, the signal to multiple far-end crosstalk ratio X em must be above 18 db and the standard deviation of the signal to far-end crosstalk ratio in db is within 9.65 db.

5. Near-End Crosstalk Coupling Loss Between Pairs in Neighboring Shielded Units

If the expected value of near-end crosstalk power between pairs in neighboring shielded units is $\overline{P_{nu}(w)^2}$ then we have the next approximate equations:

$$\overline{P_{nu}(w)^2} = k_u w e^{-\frac{4d}{\delta_c}} \quad (r_\ell \ell \gg 1)$$

$$= k'_u w^3 \ell^2 e^{-\frac{4d}{\delta_c}} \quad (r_\ell \ell \ll 1) \qquad (32)$$

where
- d : the thickness of unit shielding tape (mm)
- δ_c : the skin depth of unit shielding tape (mm)
- r_ℓ : the propagation constant of the longitudinal circuit in the unit.
- ℓ : cable length

When $r_\ell \ell \gg 1$ the near-end crosstalk coupling loss in db leads to

$$X_{eu} = -10\log\overline{P_{nu}(w)^2} = -10\log 2\pi 10^3 k_u - 10\log f + 8\cdot 28 d\sqrt{f} \qquad (33)$$

where f in kHz and shielding material is copper. From measuring near-end crosstalk coupling loss between pairs of the outermost layer in a neighboring shielded unit, we have the next experimental results:

$$X_{eu} = 130 - 10\log f + 13\, d\sqrt{f} \qquad (34)$$

where f in kHz, d in mm and shielding material is copper. From Equations (33) and (34), k_u leads to $\frac{1}{2\pi}10^{-16}$.

At the detecting point of the equalized pulse, the near-end crosstalk power between pairs in the neighboring shielded units, when there is only a single disturbing pair, is given by the next equation.

$$\sigma_{nu}^2 = \frac{1}{2\pi}\int_0^\infty \Psi(w)\,|E(w)|^2\,\overline{P_{nu}(w)^2}\,dw \quad \text{(watt)} \qquad (35)$$

where $\Psi(w)$ is the transmitting power spectrum and $E(w)$ is the transfer function of an equalizer. Fig. 10 is the numerical result of Equation (35). From Fig. 10, it is concluded that a 0.05 mm thickness of unit shielding tape (copper) is sufficient. The result is almost independent of eqalized pulse forms shown in Table 2.

Transmission Properties of The New Type Cable

Fig. 11 shows unit shielded cable sections which were studied. Each cable's far-end crosstalk coupling losses are shown in Table 3. In Table 3, $\bar{X}$ is average value in db of equal level far-end crosstalk coupling loss. Xe and Xem are, respectively, expected values of signal to crosstalk power ratio and that of signal to multiple crosstalk power ratio. σ is standard deviation in db, and S means that only a single disturbing pair exists and M means the case where all are disturbing pairs except a disturbed pair in a unit. This multiple far-end crosstalk loss is measured by the circuit shown in Fig. 12. From table 3, it is known that the following relation exists between signal to multiple far-end crosstalk power ratio Xem and signal to far-end crosstalk power ratio Xe:

$$X_{em} = X_e - 10\log n \qquad (36)$$

where n is disturbing pair number. This relation is also theoretically known, for instance, in reference 8. The frequency characteristics of cable (a) is shown in Fig. 13.

Far-end Crosstalk Coupling Loss of Cables Shown in Fig. 11

Table 3

kind of cable	shielded pair number	FXT (dB) / frequency (MHz)	$\bar{X}$ S	$\bar{X}$ M	Xe S	Xem M	Xe -10log$n$	σ S	σ M	Xmin S	Xmin M	sample number S	sample number M	measured length (m)
(a)	3	50	47.2	43.0	44.2	41.0	41.2	5.7	5.2	38.5	35.5	48	24	200
		100	42.1	39.9	39.1	36.9	36.1	6.0	5.2	32.5	29.9			
(b)	4	50	49.2	45.0	46.5	42.4	41.7	5.6	6.5	38.8	37.0	48	24	200
		100	40.9	36.2	36.9	33.2	32.1	7.0	5.1	30.0	24.8			
(c)	6 (0+6)	50	48.8	40.8	45.3	39.0	38.3	6.4	4.2	36.9	33.9	90	36	200
		100	43.1	32.6	37.5	29.9	30.5	8.2	5.6	26.0	21.8			

Considering the far-end crosstalk mechanism, it is considered that both direct crosstalk coupling and crosstalk coupling caused through a third circuit, for instance a unit shield, exist. Therefore far-end crosstalk loss degradation dependence on cable length becomes complex. Considering only direct coupling, the degradation dependence on cable length is 10 log ℓ/ℓ_0 . But the coefficient of log ℓ/ℓ_0 is really the function of ℓ_0 and f_0 , where ℓ_0 and f_0 are measured cable length and measured frequency. Table 4 shows the experimental results of far-end crosstalk degradation dependency on cable length.

Measured value of cable loss, characteristic impedance and capacitance of each cable (a), (b), (c) in Fig. 11 are shown in Fig. 14.

Experimental Results of Far-end Crosstalk Degradation Dependency on Cable Length

Table 4 $(1 \leq \ell/\ell_0 \leq 8)$

Kind of cable	ℓ_0 : 200m	f_0(MHz)
(a)	$(11.4 + 2.8 \log f/f_0) \log \ell/\ell_0$	1
(b)	$(10.3 + 4.1 \log f/f_0) \log \ell/\ell_0$	10
(c)	$(10.4 + 1.6 \log f/f_0) \log \ell/\ell_0$	1

Admissible Clock Frequency of The New Type Cable

Summarizing the foregoing studies, a survey is presented of the admissible clock frequency of the new type cables.

When using cable type (a), we take clock frequency 100 MHz and equalizer gain 90 db at 100 MHz. Then one equalizing section length becomes 1.63 km. The necessary Xe at 100 MHz of a 200 m cable length is given by the next equation.

$$X_e - 10 \log n - 17 \log \ell/\ell_0 \geq 18 \quad (37)$$

Xe becomes above 36.5 db at 100 MHz.

If we take a clock frequency of 150 MHz and an equalizer gain of 90 db at 150 MHz, then one equalizing section length becomes 1.3 km. The necessary Xe at 100 MHz of 200 m cable length is given by the next equation:

$$X_e - 10 \log n - 17.5 \ell/\ell_0 - 20 \log 1.5 \geq 18 \quad (38)$$

Xe becomes above 38.8 db at 100 MHz.

When using cable type (b), when the clock frequency is 100 MHz and the equalizer gain is 90 db at 100 MHz, one equalizing section length becomes 1.53 km, and the necessary Xe at 100 MHz of a 200 m cable length is given by the next equation:

$$X_e - 10 \log n - 14.4 \log \frac{\ell}{\ell_0} \geq 18 \qquad (39)$$

Therefore Xe becomes above 35.5 db at 100 MHz. When the clock frequency is 150 MHz and the equalizer gain is 90 db at 150 MHz, one equalizing section length becomes 1.2 km and the necessary Xe of cable length 200 m at 100 MHz becomes above 37.5 db, and the necesary Xe of cable length 200 m at 50 MHz becomes above 43.5 db.

When using cable type (c), when the clock frequency is 100 MHz and the equalizer gain is 90 db at 100 MHz, one equalizing section length becomes 1.34 km, and the necessary Xe at 100 MHz of a 200 m cable length is given by the next equation:

$$X_e - 10 \log n - 13.6 \log \frac{\ell}{\ell_0} \geq 18 \qquad (40)$$

Xe becomes above 36.2 db at 100 MHz.

When the clock frequency is 150 MHz and the equalizer gain is 90 db at 150 MHz, one equalizing section length becomes 1.08 km and the necessary X_e of a 200 m cable length at 100 MHz becomes above 38.7 db and 44.7 db at 50 MHz.

From Table 3 and the results of the above survey, it is concluded that the admissible clock frequency of cable type (a), (b) and (c) is 150 MHz.

Realizable Transmission Capacity in One Cable

In the above discussion, the admissible clock frequency is 150 MHz and the admissible highest pair number in a shielded unit is 6. So we are able to design the new type cable when conductor diameter is varied under the limitation of the cable diameter being within 71.5 mm. The result is shown in Table 5. But, when the conductor diameter is small, the problem is the repeater size and it's cost. Therefore, it is hoped that a small size and cheap reapeater will be developed. Table 6 shows the repeater properties used in the PCM-100M system experiments. The return crosstalk coupling loss between the output and the input of the repeater is above 110 db at 100 MHz.

Transmission Capacity vs Conductor Diameter

Table 5

Cable outer diameter		71.5 mm			reference
Cable sheath		stalpeth			1.2 mm: shielded pair number 4, unit number 12 0.9 mm: shielded pair number 6, unit number 14 0.65 mm: shielded pair number 6, unit number 27
Conductor diameter (mm)		0.65	0.9	1.2	
Cable loss (db/km, at 100 MHz)		94	68	59	
Characteristic impedance (at 100 MHz)		145	145	135	
Capacitance (nF /km)		29	29	33	
Number of pairs		162	84	48	
Transmission Capacity (Mb/s, one way)	100 Mb/s	16200	8400	4800	
	150 Mb/s	24300	12600	7200	

Repeater Properties [9]

Table 6

Clock frequency	f_o = 97.580 MHz
Code type	uniformed bipolar
Loss of a section	30 ~ 90 db at f_o
Level control	$\sqrt{f}$ type AGC, peak value detecting
Output pulse	3V, duty 50%
Power supply	250 mA±5%, phantom circuit is used. 12V per a repeator

Installed Experimental Line

A PCM-100M system experimental line was installed in field using cable type (a) shown in Fig. 11. The total line length is about 30 km from Musashino to Kasumigaseki and the number of repeatered links is 25. The longest single repeater spacing is about 1.5 km and the shortest is about 600 m.

Repeaters were installed for 2 systems, E-W and W-E respectively. Fig. 15 shows the repeater housing used in this experimental line.

At present, the transmission properties are being investigated and transmission experiments are being conducted.

Up to now, an about 80 km transmission through 68 repeatered links by turning up was successfull with an overall error rate below 10^{-10}.

Summary

This new type cable is considered to present an economical system, not only assuring the feasibility of digital transmission networks, but also the interconnection with FDM networks already in use. It will become one of the prospective transmission mediums in a field where large transmission capacity is required.

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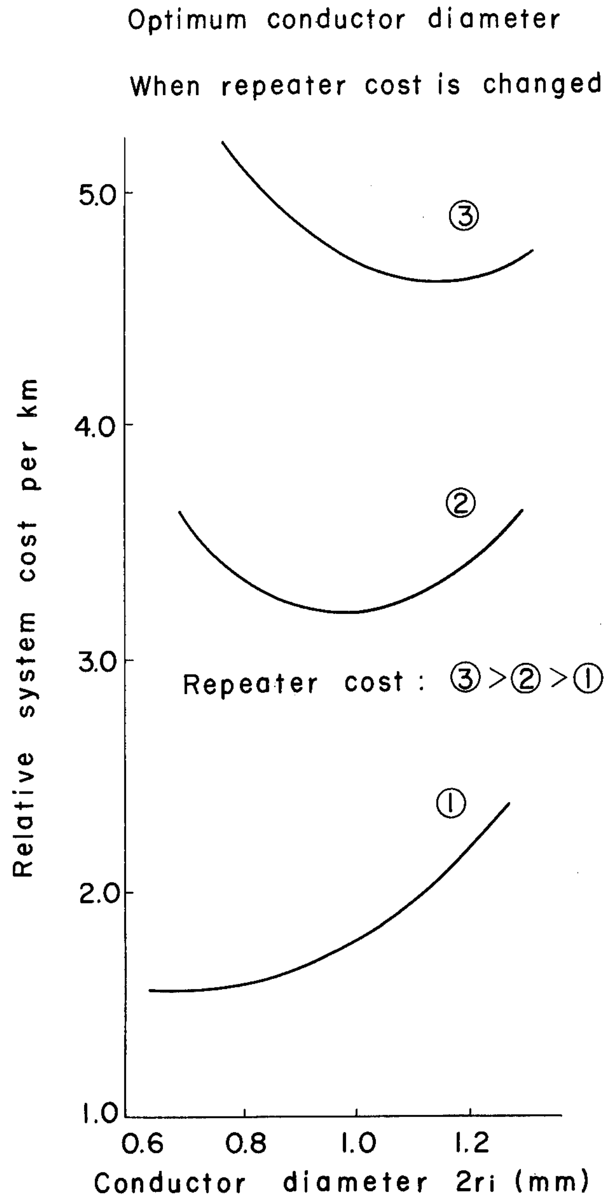


Fig. 1

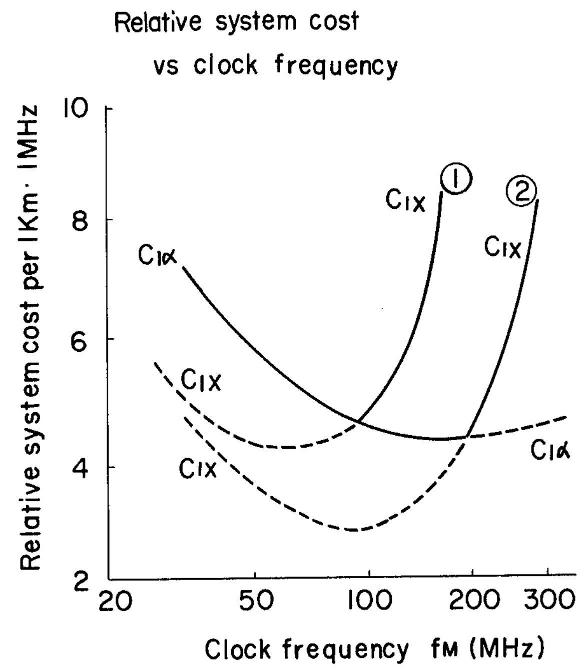


Fig. 2

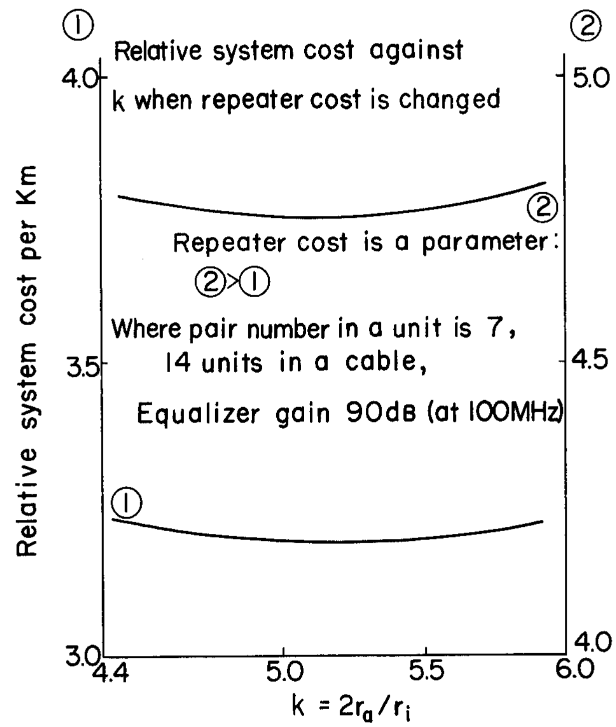


Fig. 3

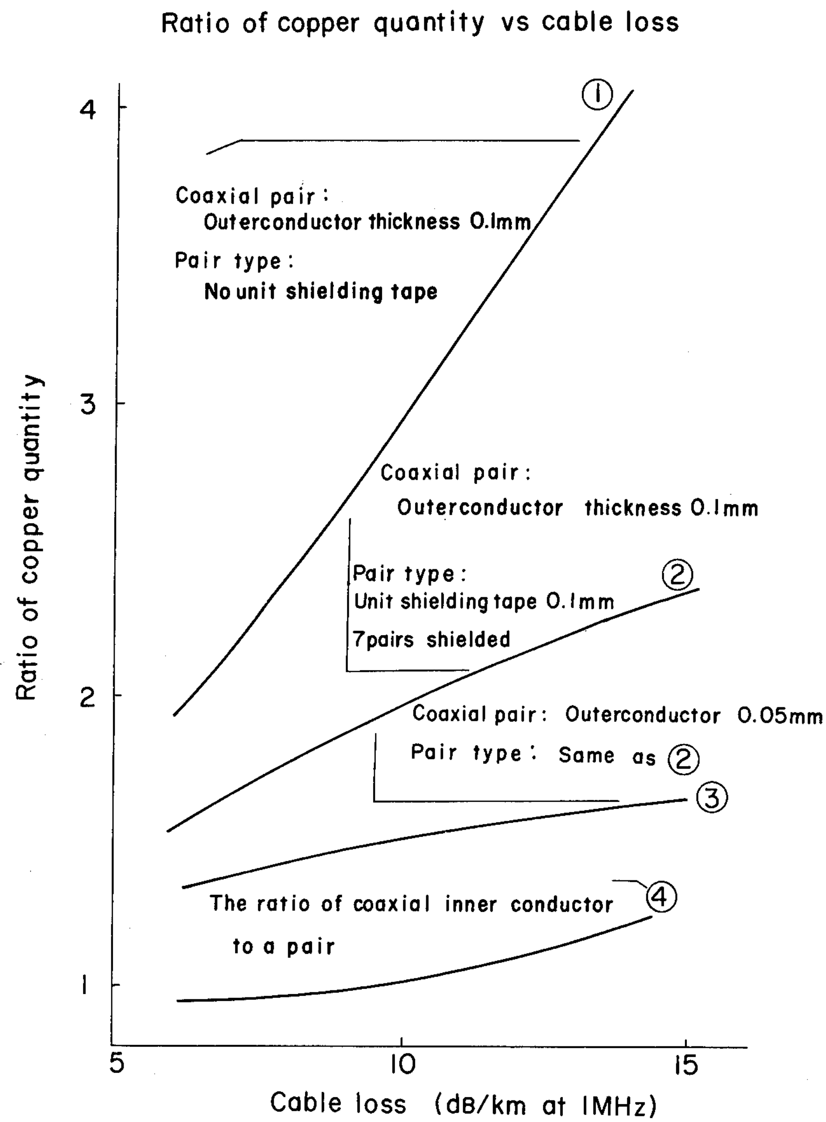

Ratio of copper quantity vs cable loss
4
3
2
1
5
10
15
Ratio of copper quantity
Cable loss (dB/km at 1MHz)
①
Coaxial pair:
Outerconductor thickness 0.1mm
Pair type:
No unit shielding tape
Coaxial pair:
Outerconductor thickness 0.1mm
Pair type:
Unit shielding tape 0.1mm
7pairs shielded
②
Coaxial pair: Outerconductor 0.05mm
Pair type: Same as ②
③
The ratio of coaxial inner conductor
to a pair
④

Fig. 4

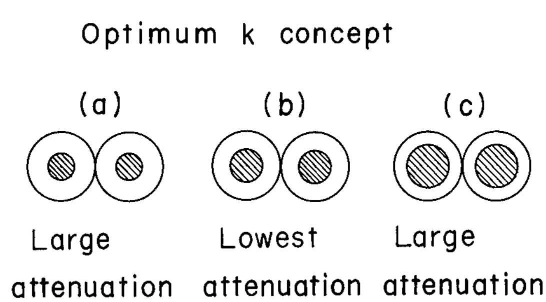
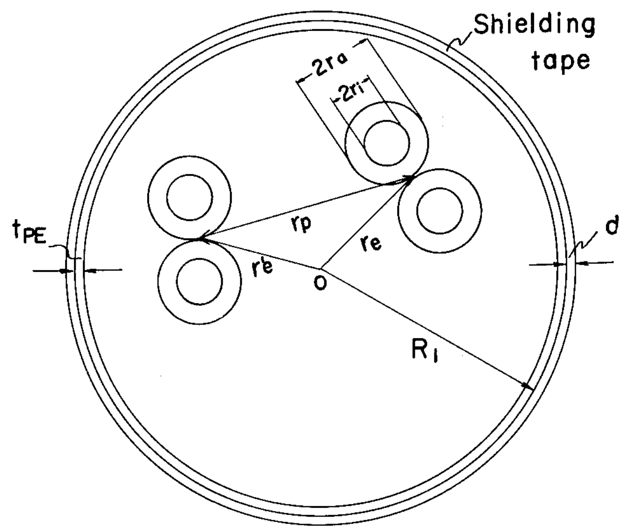

Optimum k concept
(a)
(b)
(c)
Large attenuation
Lowest attenuation
Large attenuation

Fig. 5

Parameter of each distance contained in Equation (16)



t_{PE} : Thickness of PE tape

Fig. 6

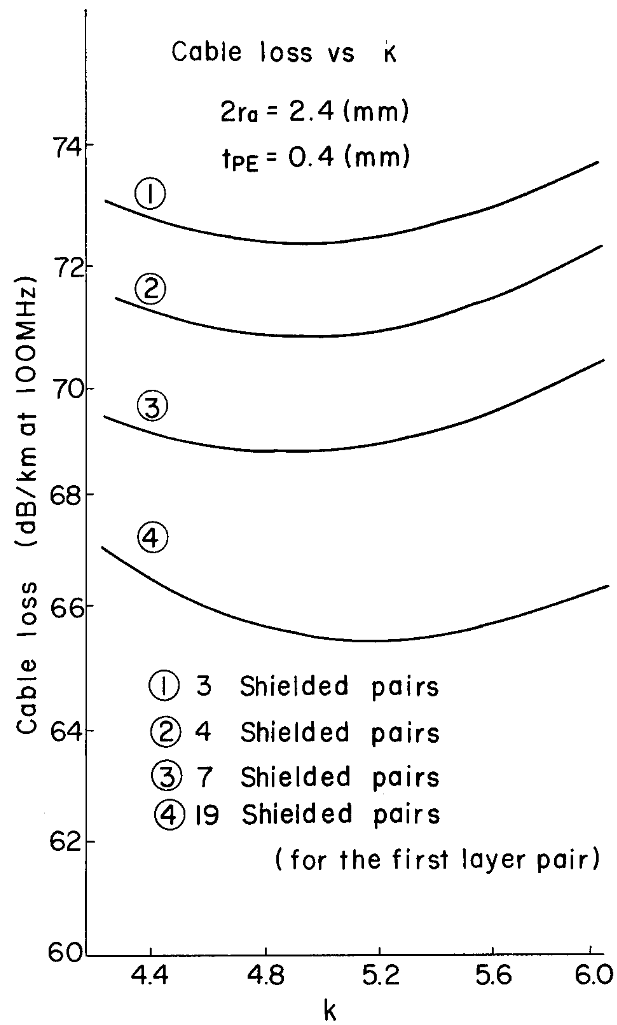


Fig.7

Error probabilities vs signal to gaussian noise ratio

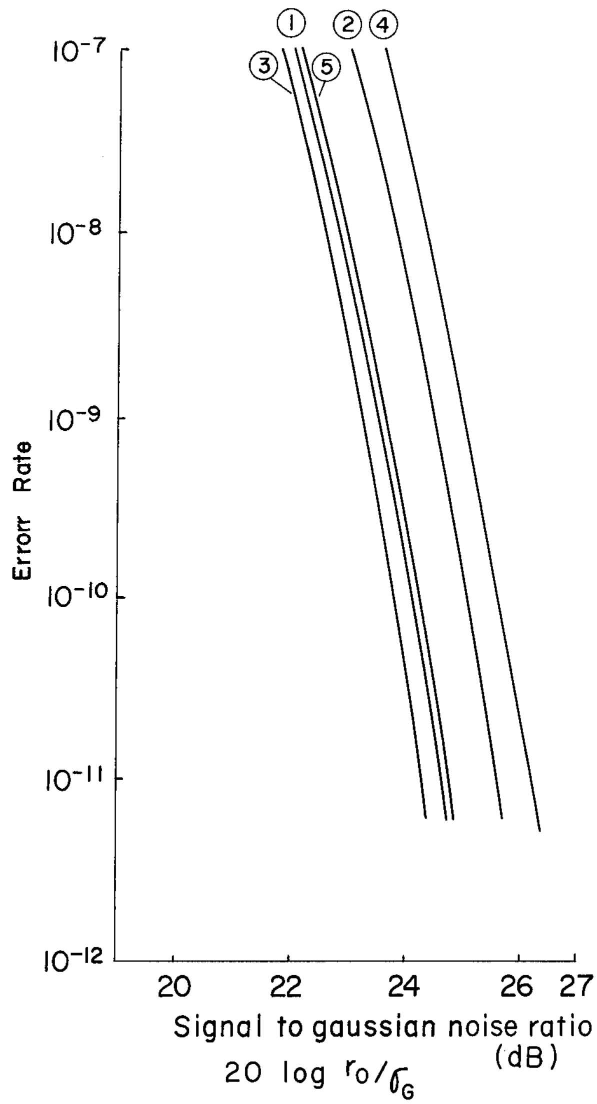


Fig. 8

Necessary signal to multiple far-end crosstalk power ratio vs one equalizing section cable loss

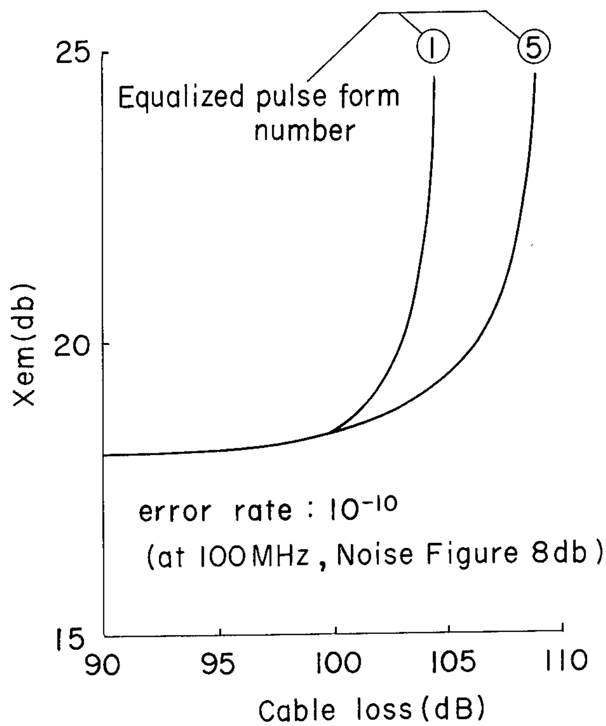
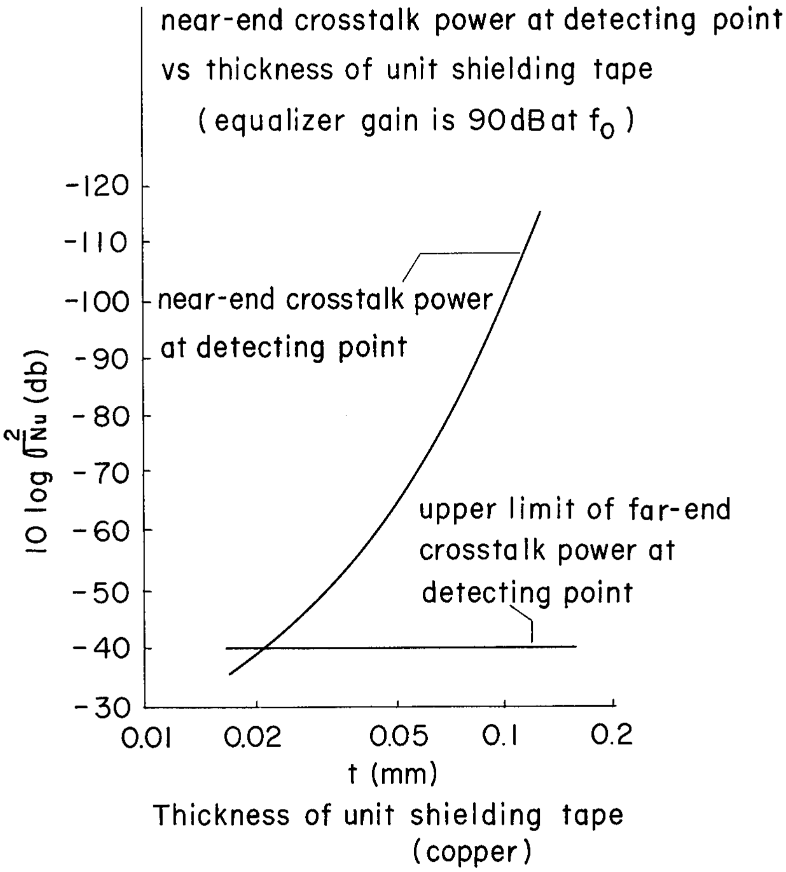


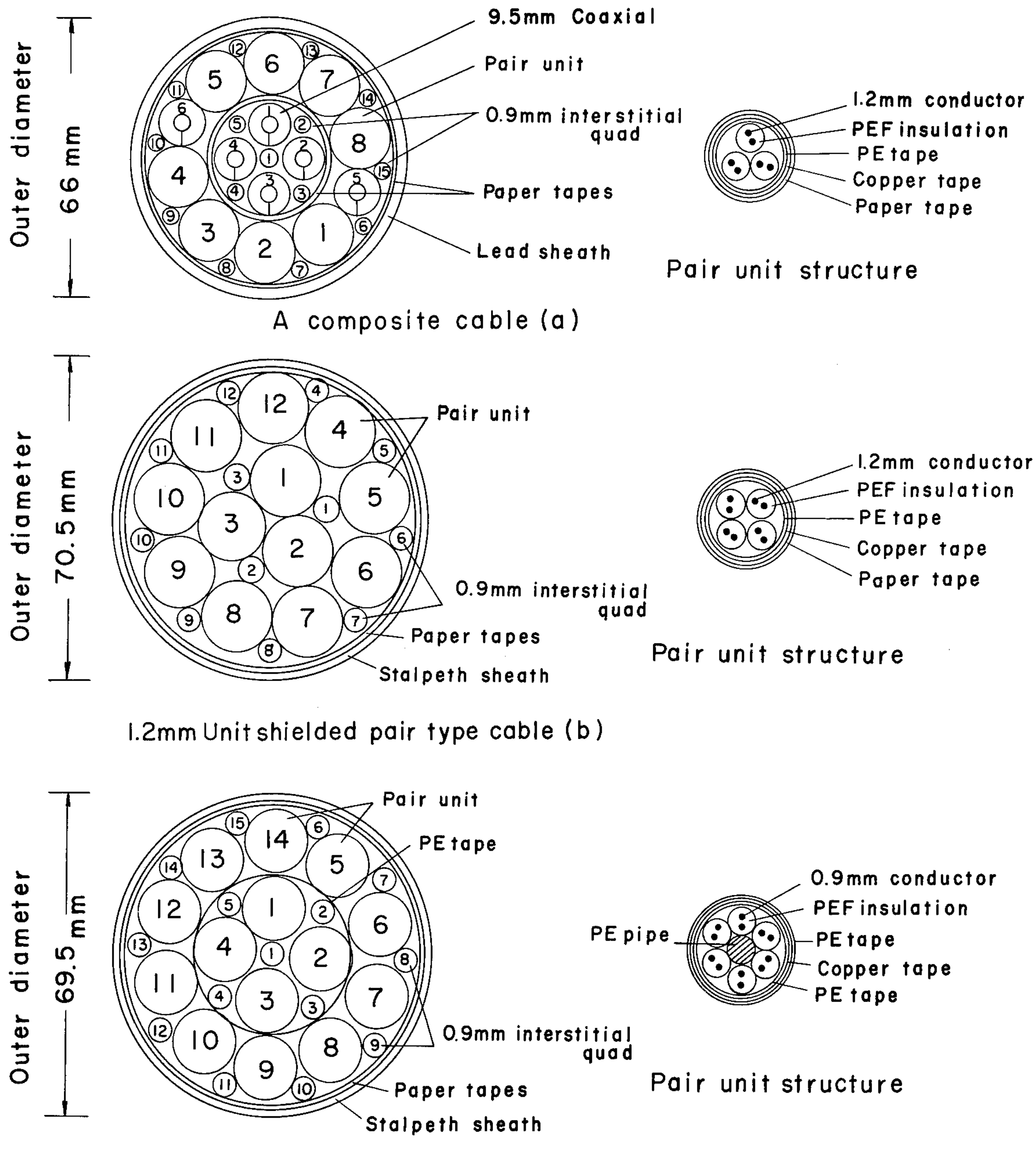
Fig. 9



near-end crosstalk power at detecting point
vs thickness of unit shielding tape
(equalizer gain is 90dB at f_0)
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
$10 \log \sigma_{Nu}^2$ (db)
near-end crosstalk power
at detecting point
upper limit of far-end
crosstalk power at
detecting point
0.01
0.02
0.05
0.1
0.2
t (mm)
Thickness of unit shielding tape
(copper)

Fig. 10

Unit shielded cable sections



A composite cable (a)

1.2mm Unit shielded pair type cable (b)

0.9mm Unit shielded pair type cable (c)

Fig.11

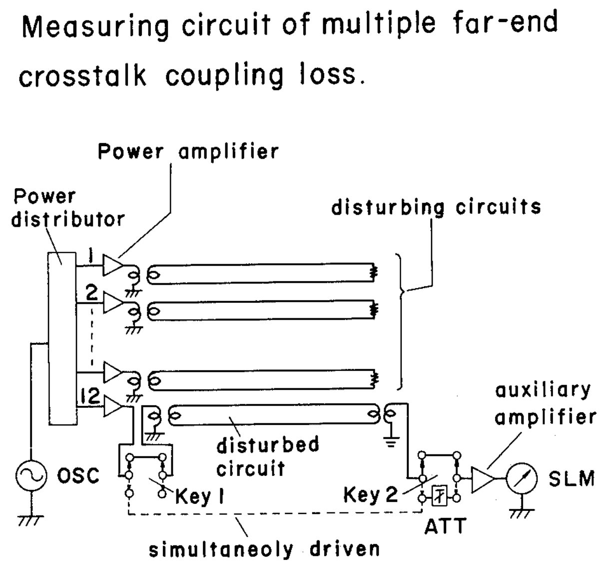


Fig. 12

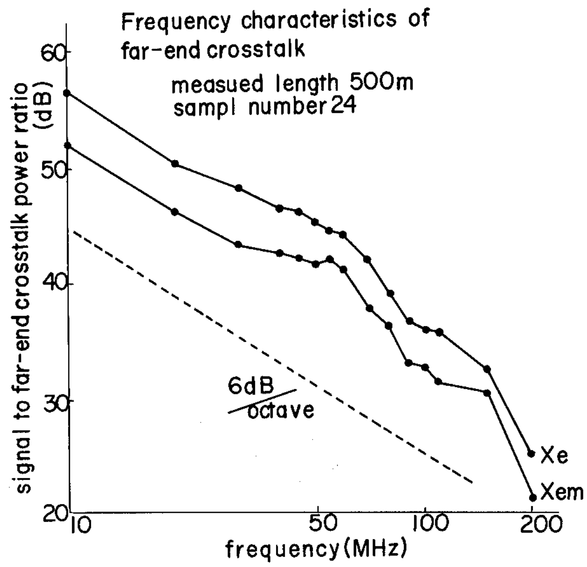


Fig. 13

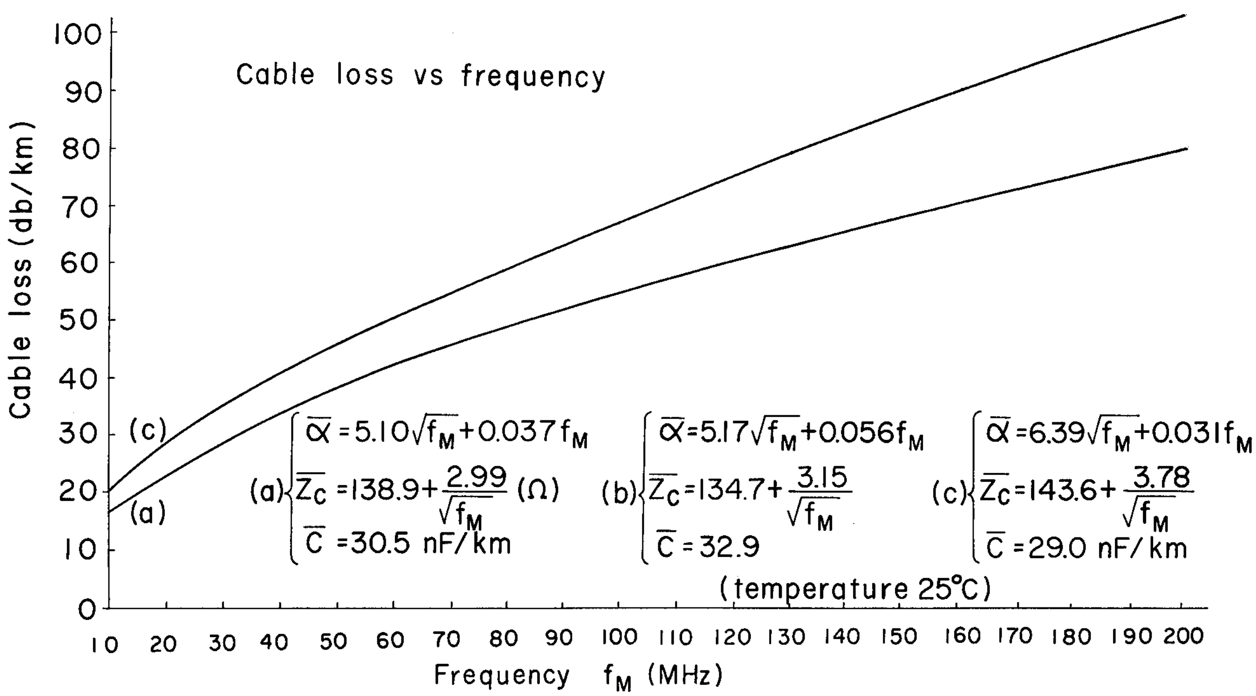
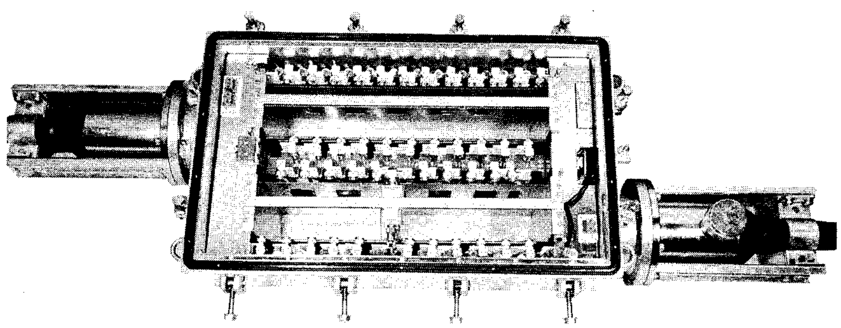


Fig.14

Repeater housing



(for 12 systems, 833x525x358(height) mm)

Fig. 15

A NEW FOAMED POLYETHYLENE INSULATED JUNCTION CABLE FOR TELECOMMUNICATION

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Summary

A new foamed polyethylene insulated junction cable has been developed to improve the electrical characteristics of traditional paper insulated cable. The new cable is now in commercial test at NTT (Nippon Telegraph & Telephone Public Corporation).
This cable consists of foamed polyethylene insulated conductors. And, the sizes are 0.4 mm 2400 pairs, 0.5 mm 1800 pairs, 0.65 mm 1000 pairs and 0.9 mm 400 pairs. The cables show that capacitance unbalances are excellent, so it has become possible for these cables to obtain satisfactory crosstalk levels without any test splices required for the paper insulated cables at each loading section.

High density polyethylene is used for insulation owing to its mechanical toughness, and can eliminate most insulation defects involved in cable manufacture and installation.

It is well known that coating a thin wall insulation with high density polyethylene is somewhat difficult due to its inferior extruding properties. The newly developed high density polyethylene insulating material, however, has superior extruding properties, and exhibits ease of extruding equivalents to that of low density polyethylene using a conventional manufacturing process. For an example, a manufacturing speed exceeding 1,000 m/min has been obtained on a 0.4 mm copper conductor with a 0.1 mm thickness and 20 % expansion.

This paper describes about the characteristics of the newly developed foamed polyethylene insulated junction cable, the results of the commercial tests and properties of the new high density polyethylene.

1. Introduction

Paper insulated and star quadded multi-pair cables have traditionaly been used by NTT for junction circuits between local exchange offices. Paper insulated cables have the following advantages, and have been finding wide uses for a long time:

-- Lower cost: The cost of insulating paper is lower than any plastic insulating material, therefore, a lower cable cost can be easily obtained.

-- Smaller cable diameter: The diameters of paper insulated cable, because of the smaller dielectric constant of paper insulation, are smaller than those of plastic insulated cable having the same size and characteristics.

-- Abundant experiance for manufacture and installation:

On the other hand, the capacitance unbalance levels of paper insulated cable are not satisfactory, and it seems very difficult to improve the characteristics further more. When junction cables are installed, test splices are made at each loading section to compensate for the capacitance unbalance. The cost of test splices accounts for more than 1% of total purchase price of junction cables, and many skilled jointers are necessary for them. It has been anticipated that a new cable requiring no test splices will be developed so that labor and cost may be saved.

Recently, plastic insulations becoming popular, many trials of plastic insulation have been made on multi-pair cables, and a great improvement of capacitance unbalance can be expected for plastic insulated cables.

When developing a new plastic insulated cable, it was thought necessary to consider the cable design from the following standpoints:

-- Equivalent characteristics: The cables must have the same size and mutual capacitance as traditional paper insulated cables.

-- Equivalent cable diameter: Smaller cable diameters are preferred for the reason of conduit conditions. It is necessary to make cable diameters equivalent to or smaller that those of paper insulated cable.

-- Low cost manufacturing: It is preferred to use conventional manufacturing processes or facilities as far as possible, and a high speed manufacturing is also required.

Owing to its excellent electrical and mechanical properties, and lower price, polyethylene is the best plastic material for insulation at present, and it has been used very extensively over a long period of time.

The dielectric constant of polyethylene insulation, however, is considerably larger than that of paper insulation. The following consideration must be paid to meet the above requirements:

-- Thin wall thickness and foaming:

-- Toughness: The insulation layer must be tough enough to prevent any insulation faulty involved in manufacture and installation.

Most of polyethylene used in insulation is low density polyethylene. As is well known, it is superior to high density polyethylene in extruding properties, but inferior in mechanical properties, and thin wall with it does not offer toughness required for cable manufacture. For these reasons, newjunction cables with thin insulation thickness of foamed high density polyethylene have been introduced.

2. Cable Construction

Changing the cable construction from star quad to pair offers lower capacitance unbalances. The star quad cables, however, have many advantages, such as cable diameter and cost for their smaller insulation diameter, high pair density and superior manufacturing efficiency at twisting stage. The new cables consist of star quads, 50 or 100 pair (25 or 50 quad) units and stalpeth sheath, having a nominal mutual capacitance of 0.050 μF/km, and they are almost equivalent to the existing paper insulated cables.

2.1 Insulation Diameter and Cable Diameter

Calculated dimensions of paper, solid PE (polyethylene) and PEF(foamed polyethylene) insulated cables having a nominal mutual capacitance of 0.050 μF/km are shown in Table 1. The diameters of solid PE insulated cable, as shown in Table 1, are too large to be installed in underground conduit, but the diameters of PEF insulated cable are equivalent to those of paper insulated cable (in NTT, the cable diameters are limited to maximum 71.5 mm). To reduce PE insulated cable diameters to an equivalent level of paper insulated ones, a thinner insulation that has been foamed adequately to make a smaller dielectric constant is necessary.

2.2 Lay-up of Quads and Units

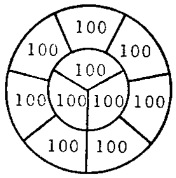
At the designing and trial manufacturing stages of the new cables, slight changes in cable make-up from that of paper insulated ones were made to get compact and symmetrical cables. For an example, a paper insulated 1000 pair cable consists of ten 100 pair units, but a PEF insulated cable consists of both four 50 pair units and eight 100 pair units as shown in Fig. 1.

Table 1 Cable Dimensions

cable size	paper insulated cable	solid PE insulated cable		PEF insulated cable		
	overall diameter	insulation thickness	overall diameter	insulation thickness	expansion	overall diameter
	mm	mm	mm	mm	%	mm
0.4mm 2400 pairs	65	0.13	72	0.10	20	65
0.5 " 1800 "	69	0.15	77	0.12	20	69
0.65 " 1000 "	68	0.20	76	0.15	20	68
0.9 " 400 "	61	0.27	72	0.21	20	65

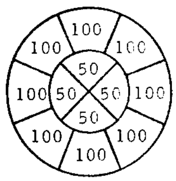
Fig. 1 Make-up of 1000 Pair Cable

(a) paper insulated cable



'100' means
100 pair unit

(b) PEF insulated cable



'50' means
50pair unit

'100' means
100pair unit

2.3 Electrical Shield and Jacket

The PEF insulated junction cables used for commercial tests are stalpeth sheathed cables, the same as the existing paper insulated cables, and an application of a laminated aluminum polyethylene sheath is also under consideration.

3. Properties of Polyethylene for Insulation

3.1 Physical and Mechanical Properties

The new polyethylene is a high density polyethylene (0.947 grams/cu.cm). When developing the new polyethylene, the major problem was to improve extruding difficulties with previous HDPE (high density polyethylene) and obtain extruding properties equivalent to LDPE (low density polyethylene). Physical and mechanical properties of newly developed HDPE having high flow characteristics (HIGH FLOW HDPE) are illustrated in Table 2.

3.2 Flow Characteristics

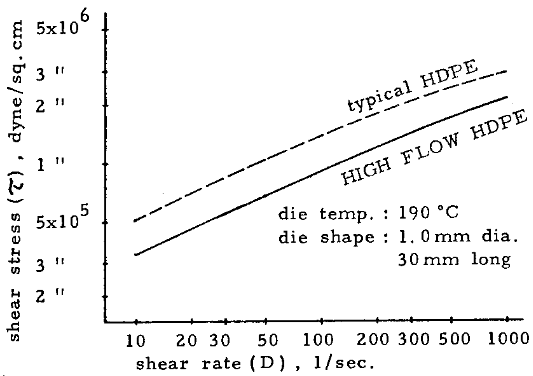
Following two figures show the flow characteristics of HIGH FLOW HDPE. (Exact extruding properties of the compound at the insulating stage will be detailed in para. 5.1.2).

The relation between shear rate and shear stress, meaning flow characteristics under high shear stress on compound, is presented in Fig. 2. They show that a sufficiently lower extruding pressure at the insulating stage will be obtained with HIGH FLOW HDPE.

Table 2 Properties of HDPE

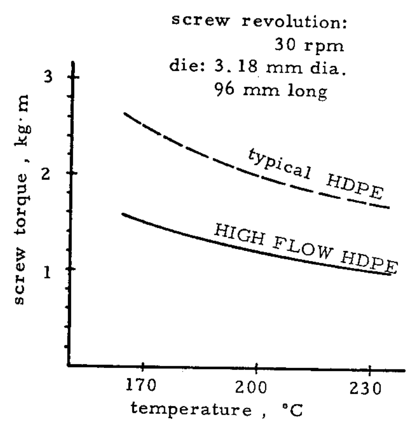
properties	typical HDPE	HIGH FLOW HDPE	testing method
melt index	0.22	0.43	ASTM-D-1238
specific gravity	0.945	0.947	ASTM-D-1505
tensile strength kg/sq·cm at yield at break	 234 247	 244 267	ASTM-D-412
elongation % at yeild at break	 19 800	 16 970	ASTM-D-412
permittivity (1MH$_Z$)	2.32	2.32	ASTM-D-150
dissipation factor (1MHz)	2.3×10^{-4}	1.0×10^{-4}	ASTM-D-150
volume resistivity ohms-cm	4.4×10^{16}	2.5×10^{16}	ASTM-D-257
environmental stress cracking resistance (ESCR), hours	500 <	500 <	ASTM-D-1693 10% Igepal at 50°C
thermal stress cracking resistance (TSCR), hours	1000<	1000<	100°C oven, based on ASTM-D-1693
brittleness at -60°C	no failure	no failure	ASTM-D-746

Fig. 2 Shear Rate (D) - Shear Stress (τ)



The results of screw torque measured by Brabender plastograph are given in Fig. 3. They also show higher flow characteristics of newly developed HDPE.

Fig. 3 Screw Torque by Brabender Plastograph



4. Properties of Insulated Conductor

4.1 Mechanical Strength

Breaking load, elongation at break and abrasion resistance of insulation are listed in Table 3.

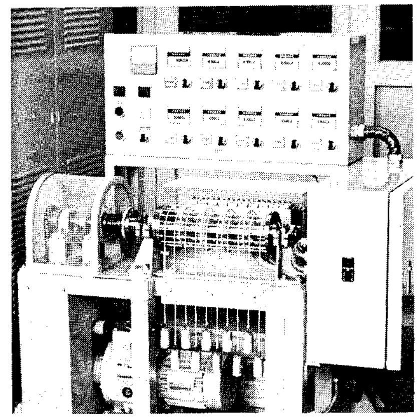
Table 3 Mechanical Properties of PEF Insulation

conductor diameter	breaking load		elongation at break		abrasion resistance	
	LDPE	HDPE	LDPE	HDPE	LDPE	HDPE
mm	kg	kg	%	%		
0.4	0.20	0.59	340	370	22	225
0.5	0.35	0.72	330	440	43	965
0.65	0.57	1.33	340	480	32	1000 <
0.9	0.75	1.58	390	460	73	1000 <

* number of allowed total cage revolution
testing load: 200g (for 0.4, 0.5mm conductor)
300g (for 0.65, 0.9mm conductor)

Abrasion resistances are measured by a cage revolution type abrasion resistance tester. The outward appearance of it is shown in Fig. 4.

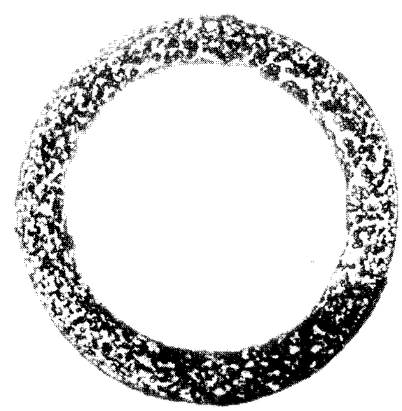
Fig. 4 Abrasion Resistance Tester (Cage Revolution Type)



4.2 Surface Smoothness and Cell Structure

The diameter and shape of cells have a relation to the surface smoothness, mechanical strength, and so on. The cells are preferred to have as small diameters as possible and to be independent of each other. As is shown in the cross-section (Fig. 5), the cells are independent of each other and have diameters of approximately 20 μ or less.

Fig. 5 Cross-section of PEF Insulation



4.3 Environmental Stress Cracking Resistance

All sizes of PEF insulated conductor with HIGH FLOW HDPE have been tested on both ESCR (Environmental stress cracking resistance) and TSCR (Thermal stress cracking resistance), and successful results have been obtained as shown in Table 4. The test methods of stress cracking resistance are as follows:

ESCR: Based on British Post Office Telecommunication Headquarters Specification CW 128. Six contiguous turns of insulated conductors shall be wound on a 6 mm mandrel; the ends of the wire being twisted together to prevent slackening. The samples shall not crack after immersion in a 20 % solution of Teepol CH53 at 50°C for 1500 hours.

TSCR: Twenty contiguous turns of insulated conductor shall be wound on its own diameter. The samples shall not crack after aging in a gear oven at 100°C for 1500 hours.

Table 4 Stress Cracking Resistance of PEF Insulation

properties	conductor size	previous typical HDPE	HIGH FLOW HDPE	test method
ESCR	mm 0.4 0.5 0.65 0.9	no failure " " "	no failure " " "	based on British P.O.T.H. Spec. CW 128 for 1500 hours
TSCR	0.4 0.5 0.65 0.9	no failure " " "	no failure " " "	20 turns on its own diameter at 100°C for 1500 hours

5. Manufacturing Method

5.1 PEF Insulation

5.1.1 Various Extruding Methods of Foamed HDPE

As is well known extruding HDPE is somewhat difficult;particularly a thin wall coating by high speed extrusion seems to have been almost impossible. Therefore, a coating method*1 of HDPE was developed and has been practically applied to very fine gauge (0.32 mm). It is a method for coating HDPE melted in solvent like xylene, toluene,and so on. The process has been proved to be excellent; however, it has not been so widely used because of its higher cost due to big manufacturing facilities and lower manufacturing speed.

Some new methods or modified conventional methods are now being developed. References have already made to a modified coating method*2 using powdered HDPE and solvent, a swelled HDPE extruding method *3, a solvent injection method*4, and so on. All of the new methods make the melt viscosity of HDPE lower with solvent, and they need pre-treatment of HDPE or reconstruction of manufacturing facilities and are not always good for operation efficiency and expenses. Various direct gas injection systems, drawing much attention, may also be applicable to the extruding of HDPE.

5.1.2 Extruding of Foamed HIGH FLOW HDPE

The extruding technique described here is an extrusion of HDPE that requires no pre-treatment of material and no reconstruction of manufacturing facilities. The process is safety in that it does not require any hazardous solvents. It is exactly the same as the conventional manufacturing process.

(a) Extruders

Exactly conventional extruders are applicable. The outline of the extruder is as follows:

Screw diameter	:	65 mm(2 1/2 in.)
Screw L/D	:	22
Type of screw	:	metering type
Compression ratio	:	3.7

(b) Manufacturing speed

Because of the lower extruding pressure by an application of HIGH FLOW HDPE, as detailed in para. 5. 1. 2 (f), the mechanical load on the extruder and back tension on running wire reduced to small and a manufacturing speed of over 1000 m/min was realized for a 0.4mm conductor. The speed is equivalent to that of solid PE insulation.

(c) Dies, Tips

A study on extruding dies shows that even shorter land dies than those for solid PE insulation provide smooth insulation surfaces and uniform cell structures. Draw down ratios from 60 to 80 percent are suitable for each gauge.

It was not necessary to make further studies on tips, the same tips used for ordinary solid PE insulation are also suitable for PEF insulation Diamond tips are employed to get a long life.

(d) Chemical Blowing Agents

Chemical blowing agents should be selected on the basis of their decomposition temperature and the melt strength of resin at extruding

temperature. For HIGH FLOW HDPE, generally used chemical blowing agents of azodicarbonamide show satisfactory results. The agents change into gases at a temperature of 160 - 190°C and one gram of them makes approximately 200 - 250 cc gases.

(e) Extruding Temperature

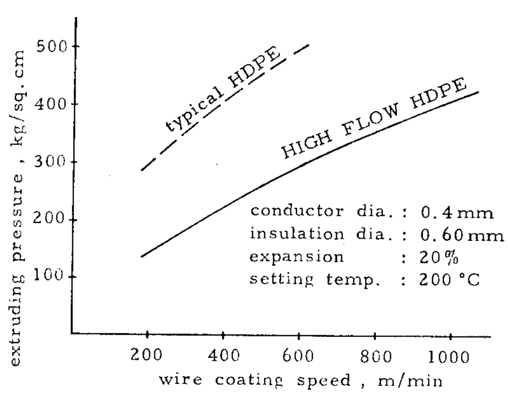
Appropriate extruding temperatures for many kinds of HDPE have been found to be approximately 200°C according to studies. An extruding temperature of 190 - 210°C makes good foams for HIGH FLOW HDPE.

(f) Extruding Pressure

As shown in Fig. 6, the extruding pressure for the 0.4 mm conductor at a line speed of 1000 m/min is approximately 400 kg/sq. cm, and it is substantially lower than that of typical HDPE, and also somewhat lower than that of LDPE. As an extruding pressure of typical HDPE becomes more than 500 kg/sq. cm at a line speed of 600 m/min, it is impossible to apply a conventional extruding technique for it.

Because of their larger die hole diameters, lower pressures are obtained for 0.5, 0.65 and 0.9 mm conductors.

Fig. 6 Extruding Pressure



(g) Wire Pre-heating

An elongation of insulation largely depends upon wire pre-heating conditions. Especially in case of HDPE, it is affected very sensitively by pre-heated wire temperature. For HIGH FLOW HDPE, a higher pre-heating temperature than that for LDPE makes good results.

5.1.3 Twisting and Stranding

A trial PEF insulated cable made from LDPE sustained many insulation defects caused at twisting and stranding stages because of its poor mechanical strength, and the manufacturing speed was forced to be reduced to low level, compared with that of the paper insulated cable. HDPE, however, can make the manufacturing speed equivalent to that of paper insulated cables without impairing insulation. A speed of 1000 rpm by double twisting type quadding machines (2000 twists per minute) is applicable to foamed HDPE insulated conductors. The manufacturing efficiency at unit stranding and cabling stages is also equivalent to that of paper insulated cable.

6. Electrical Characteristics of the Cables

6.1 Mutual Capacitance

Existing paper insulated junction cables are designed to have an average mutual capacitance of 0.050 µF/km. The new PEF insulated junction cables are designed to have the same mutual capacitance as paper insulated cables, and the results of them are shown in Table 5.

6.2 Capacitance Unbalance

A remarkable advantage of the new PEF insulated junction cables is smaller capacitance unbalances than those of paper insulated cables. The new cables have an approximately 1/3 capacitance unbalances between pairs in the same quad, comparing with the exsisting paper insulated cable, as shown in Table 6.

The relation between capacitance unbalance and cable length is not evident, but generally and simply speaking they have the following relationship:

$K = pL^q$

- K : average capacitance unbalance
- p : constant (determined by cable type)
- L : cable length
- q : constant (determined by cable type)

For an ideal cable having random couplings along the length (the couplings showing the normal distribution), the constant q should be 0.5, but actually q exceeds 0.5 for any cases because of manufacturing irregularities. For paper insulated cables in particular, the fact is that the constant q comes to nearly 0.9. An examination of the new PEF insulated cable for the relation between capacitance unbalance and cable length reveals that the constant q is approximately 0.7. Based on this fact, it can be anticipated that PEF insulation is suitable even for long cable length.

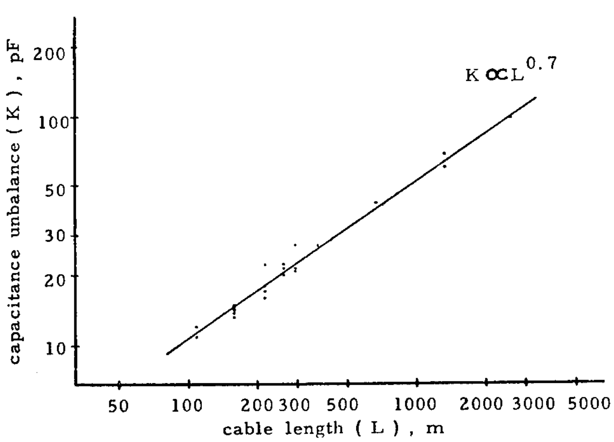
Table 5 Average Mutual Capacitance of Junction Cable

cable size	paper insulated cable	PEF insulated cable	requirements
	μF/km	μF/km	μF/km
0.4mm 2400 pairs	0.0493	0.0478	0.050 ± 0.005
0.5 1800	0.0496	0.0492	"
0.65 1000	0.0498	0.0493	"
0.9 400	0.0485	0.0485	"

Table 6 Capacitance Unbalances

cable size	cable length	corrected capacitance unbalances between pairs in the same quad			
		paper insulated cable		PEF insulated cable	
		average	individual maximum	average	individual maximum
	m	pF	pF	pF	pF
0.4 mm 2400 pairs	150	64	206	15.9	73
0.5 1800	"	54	153	15.4	75
0.65 1000	"	42	126	18.6	88
0.9 400	"	48	143	15.2	95

Fig. 7 Cable Length-Capacitance Unbalance
(0.5mm PEF insulated star quad junction cable)

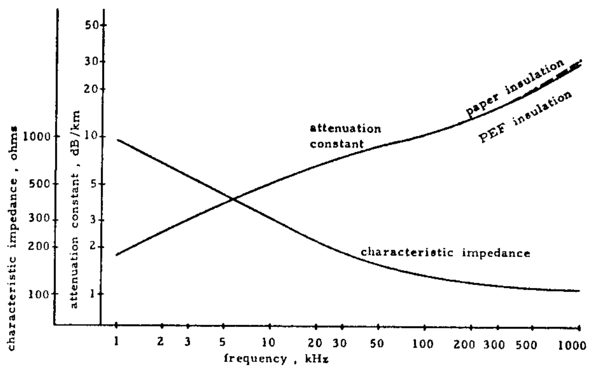


6.3 Characteristic Impedance and Attenuation Constant

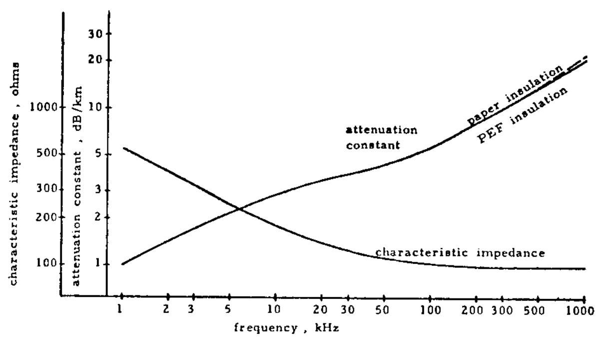
The measurements of characteristic impedance and attenuation constant of 0.4 mm 2400 pair and 0.65 mm 1000 pair cables, for example, are shown in Fig. 8(a) and (b).
PEF insulation is superior to paper insulation in high frequency characteristics.

Fig. 8 Characteristic Impedance and Attenuation Constant (Typical Values)

(a) 0.4 mm 2400 pairs



(b) 0.65 mm 1000 pairs



7. Commercial Test of New Cable

A total of 42 km of new PEF insulated junction cables, 0.4 mm 2400 pairs, 0.5 mm 1800 pairs, 0.65 mm 1000 pairs and 0.9 mm 400 pairs, are installed for commercial test that started from the autumn of 1970. The cables are jointed without any test splices.

7.1 Cost of Test Splice

Test splices are costly; for an average four jointers take two days to complete test splices of 1000 pair paper insulated cable. The cost difference between test splices and normal (straight) splices exceeds 1 % of the purchase price of junction cables.

7.2 Requirements for Capacitance Unbalance and NXT

The capacitance unbalances between pairs in the same quad for existing paper insulated junction cable are specified as follows for each cable length:

average : max. 100 pF
individual : max. 600 pF

For correction, the measured values are divided by $\sqrt{L/150}$, where L is the cable length under tests.

The paper insulated cables, after installation, are jointed with test splices at the middle point of each loading section, and with normal (straight) splices at the other points. NXT (near-end crosstalk) measurements at final test must meet the following requirements at 1 kHz:

90 % of all values	: 68 dB or better
100% of all values (worst)	: 65 dB or better

As a result of the investigation of the relation between capacitance unbalance and NXT of existing paper insulated junction cables, the following target capacitance unbalances for the new PEF insulated junction cables were found to meet the above requirements for NXT.

average : max. 30 pF/150m
individual : max. 180 pF/150m

The capacitance unbalance and NXT in loaded circuits, as is known, have the following relation*5:

$$\overline{NXT} = 188.67 - 20 \log f - 10 \log \frac{1-e^{-4n\alpha}}{\alpha} - 20 \log Z - 20 \log \overline{K}$$

where

$\overline{NXT}$	: average NXT, dB
f	: frequency, kHz
n	: number of loading sections
α	: attenuation constant per loading section, neper
Z	: characteristic impedance, ohms
$\overline{K}$	: average capacitance unbalance per loading section, pF

7.3 Resultant NXT at Final Test

The resultant NXT for 0.5 mm 1800 pairs obtained by commercial test is shown in Table 7, and it satisfies the requirements completely (para. 7.2). The results of the other sizes are now being summed up, which are supposed to be good.

As illustrated in Table 7, the NXT of the new junction cable without any test splices is equivalent to that of paper insulated one with test splices.

Table 7 Resultant NXT at Final Test

(a) paper insulated junction cable with test splices : route length 3422 m (4 loading sections)

(b) PEF insulated junction cable without test splices : route length 3554m (4 loading sections)

unit No.	(a) paper insulated junction cable		(b) PEF insulated junction cable	
	90% of all values	worst	90% of all values	worst
	dB	dB	dB	dB
1	75 or better	67	80 or over	76
2	76 "	72	76 "	73
3	72 "	68	74 "	68
4	76 "	67	75 "	73
5	73 "	67	73 "	69
6	75 "	72	73 "	69
7	75 "	72	74 "	70
8	73 "	70	90 "	75
9	78 "	75	73 "	70
10	79 "	74	73 "	70
11	78 "	74	80 "	80
12	78 "	73	80 "	80
13	81 "	74	83 "	78
14	80 "	76	85 "	83
15	80 "	72	83 "	78
16	81 "	76	81 "	70
17	77 "	71	83 "	73
18	82 "	78	83 "	73
requirement	68 "	65	68 "	65

* The measurements were made between pairs in the same quad at a frequency of 1 kHz.

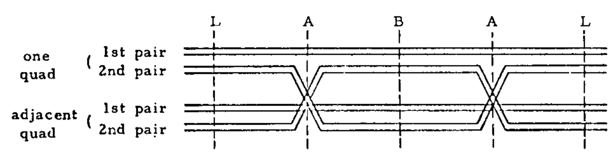
* Refer to Table 6 for capacitance unbalance of cable length.

7.4 A New Idea on Test Splice

Though the PEF insulation makes it possible to improve NXT characteristics, to get better transmission qualities, a new trial has been applied to 0.65 mm 1000 pair cables.

As shown in Fig. 9, pair transposition between adjacent quads has been made at the middle point of each half of loading section. By calculation, the trial is expected to improve NXT level by approximately 3 dB.

Fig. 9 Pair Transposition between Adjacent Quads



L : loading point
B : middle of loading section
A : middle of half of loading section
L - L : loading section
L - B (B - L) : half of loading section

Conclusion

Foamed polyethylene insulated, star quad, multi-pair junction cables having smaller capacitance unbalances have been newly developed to dispense with test splices required for paper insulated junction cables.

To have a higher pair density equivalent to that of paper insulated cable, the conductors of the cable are insulated with a thin wall of high density polyethylene to get a mechanical toughness. Not a few extruding methods for high density polyethylene have been developed to eliminate extruding difficulties involved in the material, but they call for pre-treatment of material or the reconstruction of manufacturing facilities because a solvent like xylene, toluene, etc. must be used. High density polyethylene described in this paper shows good flow characteristics at the extruding stage, so a manufacturing efficiency equivalent to that of low density polyethylene is obtained. As the result of the commercial tests to date, it is now becoming clear that test splices will be not needed for the new cables in meeting the cross-talk requirements.

Acknowledgment

The authors wish to thank the people at NTT and our associates who contributed to the development of the cable and the commercial tests of it.

Fig. 10 0.4 mm 2400 pairs
PEF Insulated Junction Cable

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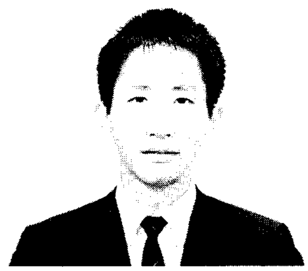

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PURE ALUMINIUM CONDUCTORS IN FULLY FILLED CELLULAR POLYETHYLENE INSULATED TELEPHONE CABLES

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Summary

Since 1969, the department of insulated wires and cables of Trefimetaux (Pechiney group) has undertaken in connection with the research center (CNET) of the French ministry for telecommunications (PTT), the study of design, manufacturing, laying and jointing of overhead and underground local telephone cables using aluminium conductors.

The use of aluminium in this field is already established in several countries, particularly in the United Kingdom, in USA and in Australia - [1 to 9], but the characteristics of the French telephone cables, particularly the star quadding and the specified level for capacitance unbalances have necessitated the development of adequate technical processes.

This report shows that it is possible to manufacture cables using pure aluminium (E.C. grade) wires of diameter down to 0.5 mm (24 AWG gauge) which have convenient electric characteristics and sufficient mechanical strength to be laid and jointed satisfactorily under normal conditions.

Main Characteristics of the French Telecommunication Local Cables

Although they are identified by the number of pairs, these cables are always twisted in star quads.

The average mutual capacitance is 50 nF/km (80 nF/mile) for all types.

They are either paper or polyethylene insulated. The water-tightness of the paper cables is obtained by a lead sheath. The screen of polyethylene cables is a longitudinally applied aluminium tape coated with an olefinic polymer which is formed around the cable just before extrusion of the outer polyethylene sheath, thus forming the moisture barrier.

The demand for local paper cables is decreasing and will be almost non-existent within a few years. For this reason, the study of aluminium as a substitute for copper was limited to polyethylene cables.

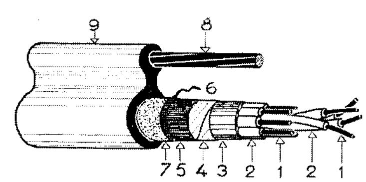
Table 1 gives the main characteristics of the local cables.

It shows that the capacitance unbalance values prescribed by the French Post Office are rather stringent, particularly for the 89 and 99 types which were recently introduced to increase the transmission possibilities of the local cables and tried with the PCM system (Pulse code modulation).

The polyethylene local cables are either overhead (25 % of total length of fabricated pairs) or pulled through underground PVC ducts.

Fig. 1

Overhead polyethylene local cable



1. Solid conductor
2. Polyethylene insulation
3., 4. and 5. Waterproof synthetic tapes
6. Tinned copper continuity wire
7. Aluminium moisture barrier
8. Steel messenger
9. Polyethylene sheath

Table 1

Main French Specifications of Local Cables

Main Characteristics \ Types of Cables	84, 85 and 87 (decreasing demand)		88 and 98 (increasing demand)		89 and 99 (high increasing demand) usable in PCM system	
Conductor diameter (mm) AWG gauge	0.4 - (0.5)-0.6-0.8-1 26 - 24 - 22-20-18		0.4 - (0.5) - 0.6 - 0.8 26 - 24 - 22 - 18		0.8 20	
Insulation	paper		Polyethylene (low density, Melt Index $\leq$ 0.5)			
Identification of insulated conductors	Coloured rings		11 colours of insulation			
Cabling element	Star Quad (with Pe threads binders)		Star Quad (without binders)			
Stranding						
- concentric	from 2 to 56 pairs and 336 pairs		8 - 14 and 28 pairs			
- units of 14 p.	-		56 pairs		56 pairs	
- units of 28 p.	112 and 224 pairs		from 112 to 1792 pairs		from 112 pairs to 448 p.	
- units of 112 p.	448, 672 and 896 pairs		-		-	
- units of 224 p.	1344 and 1792 pairs		-		-	
Screen and external protection	Type 84 : lead sheath Type 85 : lead sheath and steel tape armour Type 87 : steel sheath (welded and corrugated) and Pe sheath		Types 88 and 89 : Pe sheath (low density, melt index 0.3) on an aluminium olefinic polymer coated tape Types 98 and 99 : Pe sheath with messenger on an aluminium olefinic polymer coated tape			
Ohmic Resistance Unbalance	-		-		$\frac{\Delta R}{2R} \leq +1\%$ for 95 % of pairs $\frac{\Delta R}{2R} \leq 2\%$ for 100% of pairs	
Average Mutual Capacitance (nF/km) " (nF/mile)	50 80		50 80			
Pair to pair Capacitance Unbalance (pF)						
- for length (m) (feet)	300 985	600 1968	300 985	600 1968	300 985	600 1968
- within a quad, Average values	100	170	70	100	35	50
Maximum values	300	510	300	500	150	250
- between quads Average values	-	-	35	50	15	25
Maximum values	-	-	150	250	75	125

Description of the First Orders for Cables manufactured with Aluminium Conductors

Table 2 gives a list of the cables already manufactured by Trefimetaux GP for the French Administration. This table shows the types of cable, the quality of the metal and some manufacturing details.

The first three orders (0.63 mm,22 AWG, aluminium instead of 0.5 mm,24 AWG,copper conductors) concerned overhead cables, so that it was advantageous to exploit the lower density of aluminium and, at the same time, check the behaviour of these conductors under the mechanical stressing, inherent to overhead cables.

The fourth order provided necessary experience in pulling.

As these experimental lines were subjected to frequent inspection and control, the cheaper and simpler design was adopted : solid polyethylene insulation and moisture barrier polyethylene sheath with no filling (as for copper conductors).

These cables were laid in regions of France selected to provide a variety of climatic conditions.

Half of the fifth order, with 0.5 mm (24 AWG) aluminium conductors (equivalent to 0.4 mm (26 AWG) copper conductors) was manufactured to the same design as for 0.63 mm (22 AWG) cables, i.e. no filling and solid polyethylene insulation (Fig. 2). For the other half, jelly filling and cellular polyethylene were used. The cellular insulation was adopted in order to compensate, as far as possible, the specific inductance capacity (SIC) of the jelly without changes in capacitance and external diameter.

These cables will be pulled into ducts and their behaviour will be compared.

All the cables insulated with solid polyethylene, and consequently stranded without filling, were delivered with a dry air pressure of 0.6 kg/cm2 (8.6 lb/sq.in.).

The first two orders were particularly useful, technologically, for the selection of the best type of aluminium for this application, whilst the third order was exploited in modifying and perfecting the equipment to high-speed wire-drawing and insulation on the same line, reducing simultaneously wire breakages to an acceptable level.

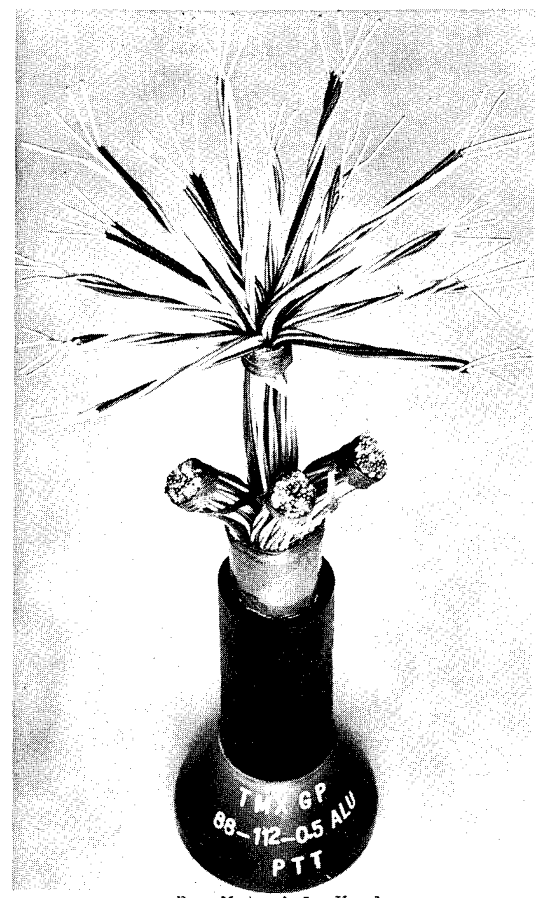
We then determined the optimal annealed wire diameter to insure, after final drawing :

- the required mechanical properties to resist fabrication-line tensions,
- an acceptable level of capacitance unbalance,
- good behaviour in jointing.

The last-mentioned order (0.5 mm aluminium wires) was, however, the most critical for it necessitated a choice :

- between commercially pure aluminium or an alloy,
- of a practical cellular polyethylene compound,
- of a filling process guaranteeing good penetration of the jelly.

Fig. 2 - 112 pairs 0.5 mm (24 AWG) Alu



Raw Materials Used

Aluminium Wires

After careful examination, we finally choose a grade of aluminium within the range employed in FRANCE for electrical applications : A5L. This grade contains more than 99.5 % of pure aluminium and less than 0.10 % of silicon.

Table 2

Aluminium Conductors in Polyethylene Local Telephone Cables

TREFIMETAUX GP Realizations up to July 1st 1971 *

	1st Order	2nd Order	3rd Order	4th Order	5th Order	
Type of Cable	56 p. 0.63mm (22 gauge) Overhead (PTT type 98)	112 p. 0.63 mm (22 gauge) Overhead (PTT type 98)		112 p.0.63mm (22 gauge) In PVC ducts (PTT type 88)	112 p. 0.5 mm (24 gauge) In PVC ducts (PTT type 88)	
Length involved (km) (miles)	3 1.9	6 3.7	7.5 4.7	7.5 4.7	4.5 2.8	4.5 2.8
Hardness of the Wire at the finished diameter	3/4 hard	3/4 hard	3/4 hard	3/4 hard	3/4 hard	3/4 hard
Insulation	Solid polyethylene	Solid polyethylene	Solid polyethylene	Solid polyethylene	Solid polyethylene	Cellular polyeth. in a fully filled cable
Successive wire-drawing and insulation on the same line	No	No	Yes	Yes	Yes	Yes

* These orders represent about half of the whole mileage of aluminium cables commissioned by the CNET program.

In all cases, 3/4 hard temper, in accordance with CNET specification CM2 and GPO specification CW 218, was adopted so that the wire could withstand the stress of extrusion line.

Table 3 gives the mechanical and electrical characteristics obtained on the 0.63 mm (22 gauge) wires before insulation.

Table 3

Diameter	mm	mini. aver. maxi.	0.627 0.629 0.630
	mils	mini. aver. maxi.	24.6 24.7 24.8
Breaking strength	kg/mm2	mini. aver. maxi.	17.5 18 18.6
	KSI	mini. aver. maxi.	24.9 25.6 26.4
Elongation	%	mini. aver. maxi.	0.5 0.8 1
Bending test	(1)	mini. aver. maxi.	7 8 9
Wrapping test	(2)	mini. aver. maxi.	3 3.6 4
Resistivity	µΩ.cm % IACS		2.737 63

(1) Bending test : on a radius of 1.5 mm (0.06") Number of bends to break

(2) Wrapping test : 10 turns on a mandrel having the same diameter as the wire and under a load of 0.360 kg (0.8 lb).

When we decided to use the wire-drawing machine installed on the extrusion line, we tried three intermediate diameters 4, 3 and 2.4 mm (0.157", 0.118" and 0.094") annealed aluminium wire. The mechanical characteristics of the 0.63mm (22 AWG) wires were comparable to those shown in table 3, except for the wire drawn from 2.4 mm (0.094") which had a lower breaking strength : 12.7 kg/mm2 (18 KSI)

On the other hand, it was possible to differentiate between the wires drawn from the 3 different diameters by the springback test (See table 4)

Table 4

Springback test	0.63 mm (22 AWG) drawn from		
	4 mm (0.157")	3 mm (0.118")	2.4 mm (0.094")
According to NEMA method (3 turns on a 47.6 mm mandrel diameter)	87	-	80
According to IEC method (5 turns on a 37.5 mm mandrel diameter)	65	62	-

We shall see in the part concerning the cable performances that there is a correlation between the results of the springback test and the capacitance unbalance.

Our choice also took into account of the number of wire breaks (low breaking strength) and the cost.

As a result, we think that 3 mm (0.118") annealed wire is the best starting diameter for 0.63 mm (22 AWG) 3/4 hard finished wire.

The problem is more difficult with 0.5 mm diameter wire (24 AWG), because its breaking strength is quite close to the tension on a high speed extrusion line.

We decided to start from an annealed 2 mm (0.079") wire originating from shaved rod. Moreover, we checked this annealed stock with an eddy current defect detector to eliminate doubtful wires before using on our drawing-extruding line.

The principle of this apparatus is as follows: The wire passes along the axis of a primary coil system, generating a high frequency alternating magnetic field. Eddy currents so produced in the wire give rise to an induced voltage in two secondary coils, placed close to the primary ones. If the wire is homogeneous, induced voltages are equal and opposed. As a result, the instrument reading is nil.

If there are irregularities in the wire, the field becomes unbalanced in the secondary coil system and the resulting voltage is indicated on a cathode screen by a point. The position of this point depends on sample characteristics and on the choice of testing frequency.

Defects in the wire cause movement of the point in different directions.

It is possible to calibrate the instrument to eliminate only unacceptable defects.

We think the use of such a control instrument is essential, to be able to use carefully small gauge pure aluminium wires, but it may become possible to find a quality of metal which makes the use of such an instrument unnecessary.

The mechanical properties of the 0.5 mm wire (24 AWG) manufactured by the process finally selected were :

Table 5

- Diameter	- mm	0.499	(0.498 to 0.501)
	- mils	19.64	(19.60 to 19.72)
- Breaking strength	- kg/mm2	13.6	(12.6 to 14.7)
	- KSI	19.3	(17.9 to 20.9)
- Elongation	- (%)	1.4	(1.0 to 1.5)
- Springback (IEC method)		49	(47 to 51)

The inlet wire for the tandem machine was stored before use in a low humidity atmosphere free from copper dust to avoid possibility of corrosion.

Solid Insulation Polyethylene

The material used was a commercial low density polyethylene with a melt index (MI2) of 0.30 g/10 min and a density at 20°C (68°F) of 0.927 g/cm3 (0.0335 lb/cu.in.). This material which has a slightly higher density than the conventional grade for insulation, provides the improved mechanical properties required for stranding and further processing.

For economic reasons, it is very important to produce an insulated wire at very high extruding speed. Melt index and density are not the only parameters contributing to smooth insulation at speeds of 1000 m/min (3 300 feet/min) and above. It is also necessary to select a polyethylene having optimum melt flow properties.

It is not the purpose of this paper to discuss all the aspects of this problem, but only to point out that the polyethylene used has a narrow molecular weight distribution ($\frac{MW}{Mn} \sim 6$) and a low amount of long chain branching.

MW (molecular weight) and Mn (molecular number) were determined from gel permeation chromatography.

Cellular Insulation Polyethylene

The material used was a low density polyethylene compound with a blowing agent incorporated by the supplier. The polyethylene basis of this compound is practically the same type as for solid polyethylene insulation.

Polyethylene Sheathing Compound

The material used was a low density polyethylene compounded with 2 % of special carbon black. The polyethylene basis density is 0.920 g/cm3 (0.0332 lb/cu.in.) and the melt index (MI2) is 0.25 g/10 mn. This very low melt index provides a good resistance stress-cracking of the sheath.

Polyethylene Coated Aluminium Tape

Laminated pure aluminium coated on one side with an extruded olefinic polymer film was used.

Two types were adopted according to sheath diameter :

Alu - PE 80/40 Aluminium thickness 0.08 mm (3.1 mils)
coating thickness 0.04 mm (1.5 mils)

Alu - PE 150/60 Aluminium thickness 0.15mm (5.9 mils)
coating thickness 0.06mm (2.3 mils)

Filling jelly

The petroleum jelly, used in the fully filled telephone cables, was a compound of a heavy hydrocarbon and a microcristalline wax.

Its specific inductance capacity (SIC) was 2.2 and its drop point 66°C (151°F) for underground cables. In the future, we shall use a compound with a drop point of 78°C (175°F) for overhead cables.

These qualities were chosen after various compatibility tests with cellular polyethylene.

The compatibility tests are described in the part concerning the cable performances.

Cable Manufacture

The aim of this chapter is to describe the manufacturing processes used for 0.5 mm (24 AWG) conductors cables. Some results on 0.63 mm (22 AWG) conductors are only given for comparison. However, the machines and technological methods used are exactly the same for 0.5 mm (24 AWG) or 0.63 mm (22 AWG) aluminium conductor cables.

Wire-Drawing

The advantages of wire drawing and insulation operations on the same line are :

- Cost reduction
- Negligeable wire oxydation, i.e. fewer defects in the spark test.
- Uniform wire diameter, i.e. better values of capacitance unbalances and resistance unbalances.

The wire-drawing insulation line used for aluminium conductors is equipped with rotating 30 inch diameter pay off drums.

The wire-drawing machine is a conventional non slip 17 dies drawing machine, 24 % theoretical elongation per die and ceramic cones.

In practice, while drawing wire from 2 mm (0.079") annealed stock down to 0.5 mm (24 gauge), we used 12 diamond dies with an elongation of about 26 % per die, and with a small amount of slip.

A special oil for aluminium (Aludraw N° 8) was used as lubricant and oil temperature was maintained under 50°C by means of a cooler, on the circulation system.

Before processing aluminium, the tandem line was carefully cleaned, particular attention being given at the wire drawing machine to remove copper dust which could cause corrosion of the aluminium.

The mechanical parts of the line were checked and replaced where necessary to reduce the friction in moving parts and thereby minimize the tension applied to the conductor during insulation. The 0.5 mm conductor (24 gauge) breaks at a tension of 2.5 kg (5.5 lb).

Polyethylene Insulation

Our tandem lines were equipped with 65 mm ($2\frac{1}{2}$ inches) extruders, length of the screw : 20 diameters, air cooled.

A diamond tip and a three angles die, centred by screws, were adopted.

The extruding temperatures were :

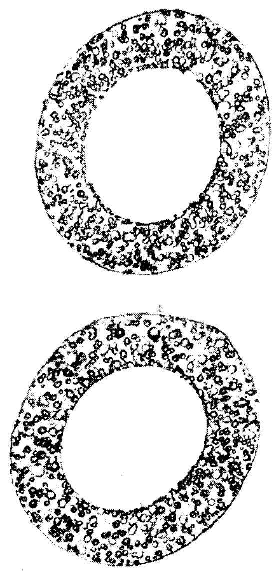
	Solid Pe	Cellular Pe
Barrel	270/290°C (518/554°F)	180/200°C (356/392°F)
Head and Die	300°C (572°F)	210/230°C (410/446°F)
Screw cooling water	40°C (104°F)	40°C (104°F)

Wires insulated with solid polyethylene were water-cooled at a distance of 2.5 m from the die, while in the case of cellular polyethylene insulation, this distance was reduced to about 1 m.

The solid polyethylene insulated wires were checked with a 50 Hz spark tester (3 500 V) and the cellular polyethylene insulated wires with a capacitance monitor. For both, we used a diameter measuring device.

The SIC value of our cellular insulation was 1.9 (Fig. 3)

Fig. 3



Regular and homogeneous expansion was ensured by preheating the aluminium wire, using an induction preheater equipped with aluminium alloy pulleys to improve electric contacts and avoid corrosion (Fig. 4)

Fig. 4

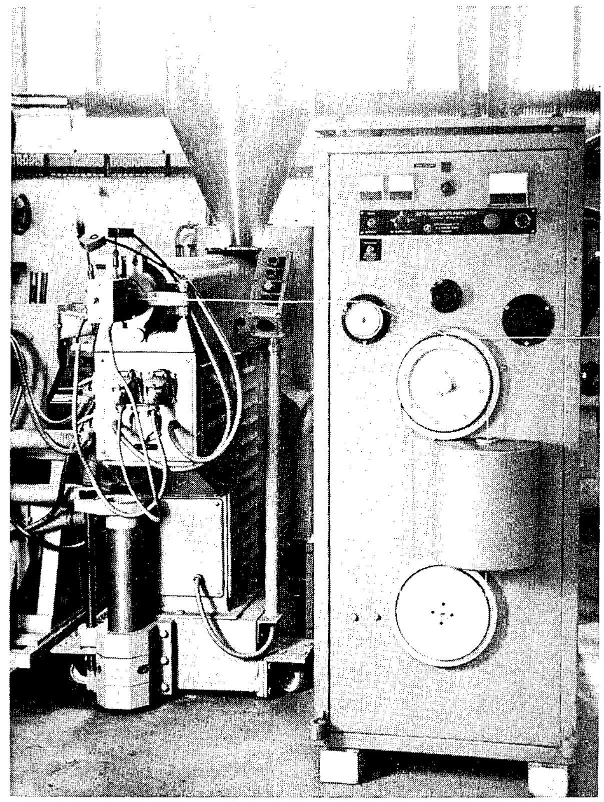


Table 6

Conductor (mm)	0.5 copper (24 AWG)	0.63 alu (22 AWG)	0.5 alu (24 AWG) Solid Pe insulation	0.5 alu (24 AWG) cellular Pe insulation
Wall thickness (mm) (mils)	0.14/0.16 (5.5/6.3)	0.17/0.20 (6.7/7.9)	0.14/0.16 (5.5/6.3)	0.15/0.175 (5.9/6.9)
Line speed (m/mn) (feet/mn)	1200/1400 4000/4600	1000 3300	700 2300	700 2300
Running tension (kg) (lb)	4 9	3.6 8	2 4.5	2 4.5
Number of wire breakages per 100 km (62 miles)	0.8	1.2	3.2	3.2

Line speeds, running mechanical tensions and average number of breakages are summarized in the Table 6.

Taking account of the more delicate adjustments (concentricity, diameter, capacitance) and of longer stabilization times, the production rate of cellular insulated conductors is estimated to be 20 % below that production rate of solid insulated conductors.

The take-up operation with automatic change of drums is an important cause of breakages. It is necessary to have a perfect synchronisation of the empty drum start speed with the line speed and to avoid any snatching from the transfer finger.

Quadding

All our solid insulated conductors were quadded on machines with double twist at a speed of 1200 to 1500 lays per minute.

Our lay range was between 55 and 85 mm (2.16" and 3.34").

The first half of the cellular polyethylene insulated conductors were quadded as above. The other half was quadded on a lower back twist machine at a speed of 370 lays per minute.

In the part concerning the cable performances, it will be seen that the capacitance unbalance results are very different.

The tension on the insulated conductors was adjusted to 0.3/0.4 kg (0.66/0.88 lb).

Stranding

The 4 units of 14 quads were stranded in one operation on a drum twister machine with fixed pay-off stands and rotating capstan.

The tension on the quads was about 2 kg (4.4 lb)

The belt of the unfilled cables consisted of three synthetic tapes, that of the jelly filled cables of two crepe papers.

Filling (only with cellular insulation)

Various techniques are known to fill cables. For our first order according to this design, we chose the same means and a similar process as those currently used to dry and to impregnate paper power cables.

After the stranding operation, the cables were placed in a steam heated tank under vacuum, the temperature being limited to 60°C (140°F), 12 hours later the preheated jelly was admitted.

After filling the tank, a pressure of 3.5 kg/cm2 (50 lb/sq.in.) was applied to the compound during 3 hours. After 6 hours of cooling under pressure, the tank was brought back to the atmospheric pressure. We now think that a pressure of 1.5 or 2 kg/cm2 (21 or 28 lb/sq.in.) would be sufficient.

The total cycle was about 23 hours. We could treat 15 km (9.3 miles) of 112 pairs 0.5 mm (24 AWG) cable per cycle.

This method is perhaps more expensive than a continuous filling process on the stranding machine, but we think it has the following advantages :

- working in vacuum ensures the elimination of humidity,
- jelly penetration is complete, even at the center of the quads,
- pollution of machines, workshop and workers by jelly is very limited.
- There is no limitation to the use of compounds with a higher drop point.

Sheathing

The laying of a longitudinally applied aluminium polyethylene coated tape and simultaneous extrusion of the outer polyethylene sheath (possibly together with a steel messenger) is carried out by a conventional process under the same conditions as for existing copper cables.

With a 150 mm/18 D (6"/18D) extruder, the line speed is 15 to 20 m/mn (50 to 65 feet/mn) on cables of the type described above.

When the cables are jelly filled, a dry crepe paper is also longitudinally applied on the sheathing line just before the coated aluminium tape.

This paper tape traps the excess of jelly before passing through the extruder head. In this way, leaks of jelly between the moisture barrier and the sheath are avoided and the adhesion of the aluminium tape is not affected. Then, the heat supplied by the sheath provides a good impregnation of the paper and a good penetration of the jelly up to aluminium barrier.

Table 7

Capacitance Unbalance in Terms of Springback

Conductor (Solid PE insulation)	Annealed copper 0.5 mm (24 AWG)	Alu (3/4 hard) 0.63 mm (22 AWG)					Alu (3/4 hard) 0.5 mm (24 AWG)	Required Values (PTT type 88/98)
Capacitance Unbalances pair to pair pF/300 m (pF/985 feet) — mean values	26	60	59	74	77	81	51	70
maxi 95 %	90	165	160	190	210	210	140	200
maxi 99.9 %	220	350	330	360	430	430	280	300
Springback test (1)								
NEMA	74	80	81	84	87	-	-	-
IEC	-	-	-	-	-	65	53	-
Tensile strength-kg/mm2	25	12.7	16.6	17.1	14.2	15.4	15	-
-KSI	36	18	23.6	24.3	20.2	21.9	21.3	
Elongation - %	20/23	0.9/2.1	0.5/1.5	0.5/1.0	1.0/2.2	1.0/2.0	1.0/2.0	-

(1) Since 1970, springback test is in accordance with IEC

NEMA MW 2.1959 - Mandrel dia. 47.6 mm (1.87") - load 113 g (0.25 lb) - 3 turns

IEC 55 - Mandrel dia. 37.5 mm (1.47") - load 1200g (2.64 lb) - 5 turns

Cable Performances

Initial trials on 0.63 mm Conductor Cables

For telephone cables, among essential characteristics, pair to pair capacitance unbalance is particularly important.

This characteristic is influenced by the regularity of insulation processing : good concentricity and uniformity of wire and insulation diameters.

On the other hand, it is also known that the quadding technique is important : back twist quadding (slow speed) produces an improvement of capacitance unbalance, but increases the cost.

Although conditions are the same as for copper conductor cables as regards uniformity of sizes and quadding method, the capacitance unbalance obtained on aluminium conductor cables is about doubled.

Together with previous comments, these remarks point up the important influence of wire stiffness. The usual elongation measurements do not necessarily differentiate the various grades of final wire ; however, such wires may have different springback values and one then finds a correlation with capacitance unbalance measurements. (See Table 7).

Values of capacitance unbalance were practically the same on cables, made either from wires drawn on the tandem line or wires drawn separately.

Excellent values of resistance unbalance (+ 0.25 %), as for copper conductor cables result from tandem drawing/insulation operation.

0.5 mm Conductor Cables

The results of springback and capacitance unbalance obtained with the 3/4 hard drawn 0.5 mm (24 AWG) aluminium wire of the last order confirm the correlation mentioned above.

The 0.5 mm (24 AWG) wire springback is lower than the 0.63 mm (22 AWG) wire springback. The capacity unbalance is also lower (See Table 8).

These results show that pure aluminium (EC grade) in 24 gauge size (0.5 mm) is suitable and that it is possible to produce cables to different PTT specifications (either 88 or 89 types).

Results obtained depend on the quadding method.

In future, the use of an alloy may be considered. This might show advantages in processing (less breaks, higher extrusion speeds) and in subsequent use of the cable, provided that an increased springback did not lead to further capacitance unbalance. In any event, the final issue would be decided by cost.

Particular Characteristics of Jelly-Filled Cables

Compatibility of insulation with filling : An important requirement for this type of cable necessitates that no long term deterioration of insulation should be produced by the filling compound. Thus various tests were carried out :

- Mechanical properties of cellular insulation (British Post Office specification M 142).

  - Preliminary examination

	Measured	Required
Elongation %		
mean value	420	-
mini	310	250
Breaking load		
mean value		
g.	340	-
lb.	0.75	-
kg/cm2	90	
lb/sq.in.	1280	

	Measured	Required
Breaking load		
mini		
g.	230	200
lb.	0.50	0.44
kg/cm2	63	-
lb/sq.in.	896	

  - After ageing test :

A sample of the completed cable was heated for 14 days at 60°C (140°F) : elongation values were practically unaffected, whilst breaking loads fell by only 10 %.

- Winding test (German Post Office specification FTZ 72 TV1) :

Lengths of insulated conductor, carefully removed from a sample of completed cable aged in an oven for 7 days at 70°C (158°F) were wound on a mandrel of the same diameter.

There was no evidence of splitting after 24 hours at 70°C (158°F).

- Watertightness :

Our cables were tested to PTT specification (the same as German Post Office specification FTZ 72 TV1) :

A water pressure of 1 metre is applied to one end of a sample of 1 metre long for 7 days ; after this time, no water must have appeared at the other end.

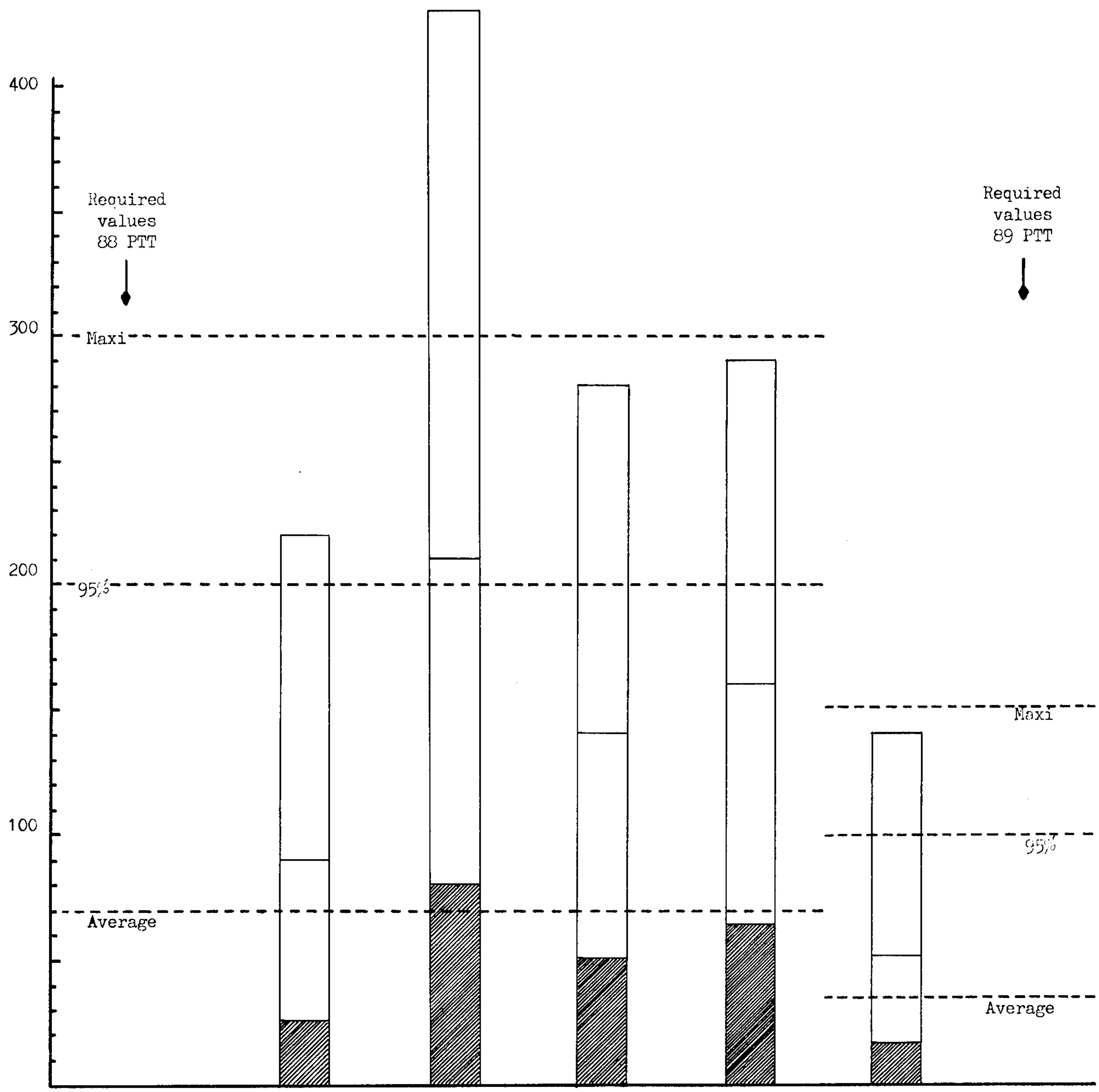
Effect of filling on the insulation resistance: Filling jelly increases the charge time-constant (phenomenon of dielectric absorption in the case of composite insulations) and influences the insulation results.

The following values were obtained :

	Required (CW 218B)	Measured		
Electrification time (mn)	1	2	4	10
Insulation resistance (MΩ/Km)				
Mean value	-	8 400	13 500	37 500
Mini value	1 600	6 500	10 000	31 500
MΩ/Mile				
Mean value	-	5 200	8 400	23 300
Mini value	1 000	4 000	6 200	19 500

Table 8 - Capacitance unbalance (pF/300m)(pF/984 feet)

Metal	Cu	Al	Al	Al	Al
Diameter (mm) (gauge)	0.5 24	0.63 22	0.5 24	0.5 24	0.5 24
Insulation PE	Solid	Solid	Solid	Cell.	Cell.
Quadding - Double torsion high speed	X	X	X	X	
- Back twist low speed					X



Jointing Processes and Laying Operations

Connections between two Conductors

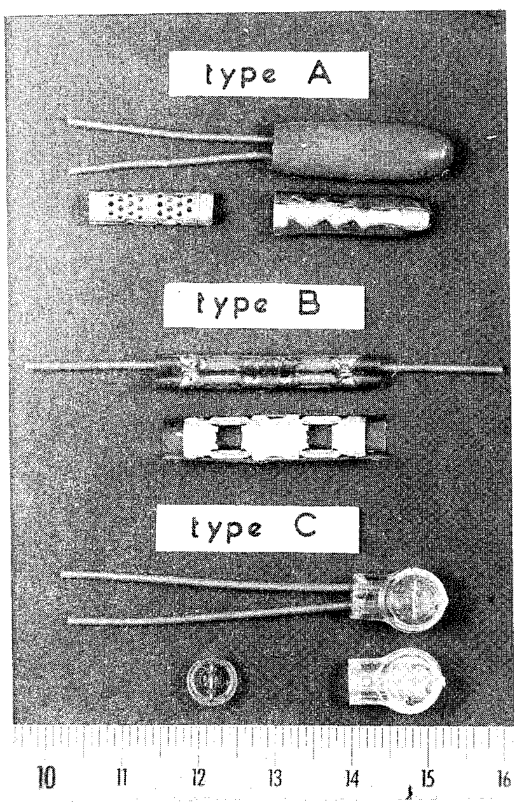
Corrosion risks and mechanical characteristics of the 3/4 hard aluminium conductors (small elongation and limited bending possibilities) have necessitated special study of jointing techniques.

The technique used in France for copper conductors : twisting of the two bare wires (pig tails) was not possible with aluminium conductors.

Wishing to avoid any risks of damaging conductors and insulations, we looked for connectors involving no removal of the insulation.

A programme of tests was undertaken jointly by the laboratories of CNET and Trefimetaux GP, which involved trials on various crimped connectors. Fig. 5 shows three types among these.

Fig. 5 : Tried Connectors



A and C connectors are delivered filled with grease (or jelly).

A special tool, different for each connector, is used to achieve mechanical tightening and electrical connection.

Tests were carried out on copper-copper, copper-aluminium and aluminium-aluminium connections.

5 to 30 junctions of each type were subjected to the following trials :

- behaviour under wet and hot conditions :
  - 30 cycles of 8 hours at + 50°C (122°F) and 16 hours at + 30°C (86°F)

    to check the contact resistance
- thermal shock :
  - 10 cycles of 4 hours at - 30°C (- 22°F) and 4 hours at + 70°C (158°F)

    to check the contact resistance
- dry and hot conditions :
  - 4 cycles of 1 hour at 100°C (212°F) and 23 hours at 20°C (68°F)

    to check the contact resistance

insulation resistance :

- connectors without jelly (for instance : Type B) :
  - voltage : 500 Volts DC
  - application time : 1 minute

  to check the insulation resistance between the wires of two connectors bound together.
- connectors with jelly filling : (for instance : Types A and C) :
  - joints immersed for 30 days in water (room temperature)
  - voltage : 500 Volts DC
  - application time : 1 minute

  to check the insulation resistance, each week, between conductors and water.

- breaking strength :

The breaking strength of the jointed conductors was measured by pulling on the two conductors, up to breaking point.

- constant tensile strength :

A load of 0.6 breaking strength was applied between the two jointed conductors during one hour, the contact resistance was then measured.

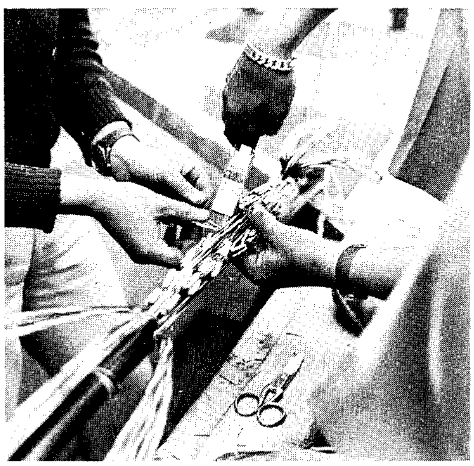
- vibration tests (only in the CNET laboratories)

The vibrations were obtained by frequency cycles (from a few hertz to 40 hertz) with a total amplitude of 1.5 mm (0.059") and were applied for 40 mn to each of 3 orthogonal axes.

The electric resistance was again measured.

The results of these trials showed that the behaviour of the various types of connectors was the same with copper-copper connections. On the contrary, with copper-aluminium and aluminium-aluminium junctions, design and mechanical tightening had an important influence on the reliability of the connections. The best results were obtained with Type A. This type was chosen for the jointing operations on the first links (See Fig. 6).

Fig. 6



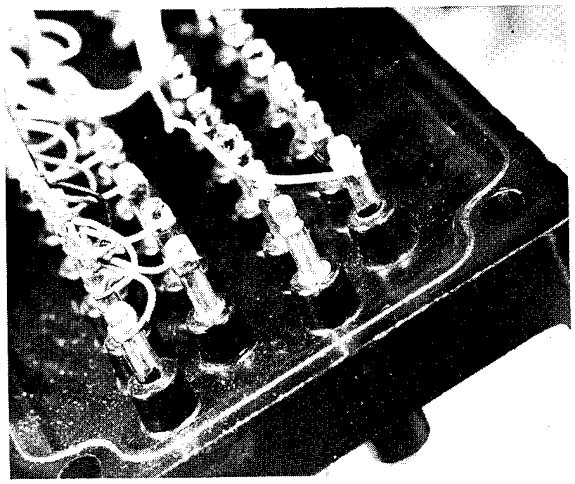
When all connections were completed, the group of units was covered with PVC tape. The external sheath was reconstituted using a thermoshrinkable tube internally coated with bitumen. In this way, the whole cable is perfectly watertight.

A crepe paper lapped on the PVC tape forms a thermal protection and prevents the flow of bitumen onto the connections.

Connections between a Conductor and a Clamp of a Cabinet or a Pillar

The aluminium conductor carefully stripped with a special tool, was wrapped (2 turns) around the pin of the clamp using the same method as for copper. It was then soldered by a soldering iron using a solder incorporating a special flux. (See Fig. 7).

Fig. 7



Tests were made at a sea-side installation to establish a possible need for protection by a varnish or silicone grease.

After two years, no corrosion appears on protected or unprotected connections.

Laying Operation :

The French National Center of Telecommunications Studies decided to lay the overhead cables (56 and 112 pairs of 0.63 mm aluminium conductors) in areas where the climatic conditions are particularly severe (wind, salt spray, etc....)

The first line was installed in January 1970 at the sea-side, near Nice ; after that, other lines were laid in Provence and in Brittany also at the sea-side, and still another near Chambery, in a mountainous region. (See Fig. 8, 9 and 10).

Several buried lengths were also installed in Brest (Brittany), the cables being pulled in PVC ducts of 80 mm (3.15") diameter.

With both types of cable, the laying operations were easier than with copper cables due to the reduced weight.

The workers were quickly accustomed with the new jointing processes.

The cables with 0.5 mm (24 AWG) conductors remain to be laid.

Fig. 8

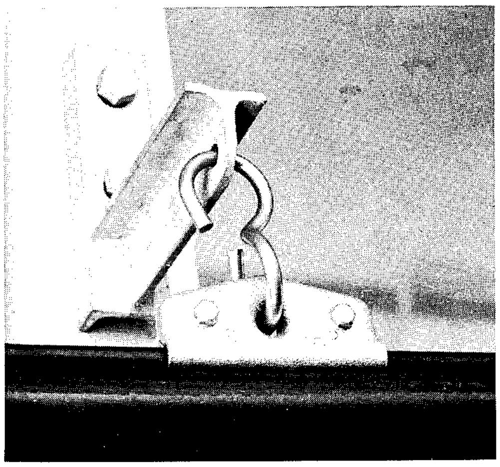


Fig. 9

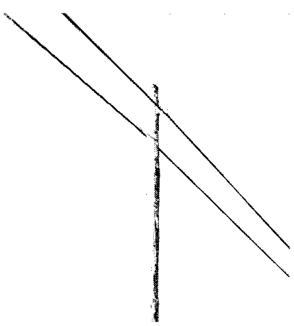
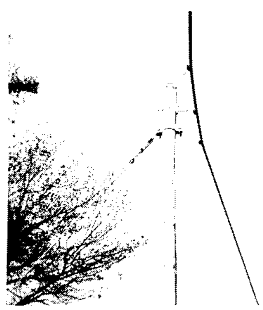


Fig. 10



Conclusion

EC grade Aluminium conductor, even in 24 gauge size, can be drawn and insulated with cellular or solid polyethylene on high-speed production lines.

The cables, made of star quads and eventually filled with a compound to exclude humidity, may be made with almost the same electrical characteristics as equivalent copper cables. Reliability is obtained through careful control of metal quality (possibly improved in the future by special processing of the raw material), effective protection against corrosion and well-adapted jointing processes.

Acknowledgments

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EVALUATION OF THERMAL DEGRADATION IN POLYETHYLENE TELEPHONE CABLE INSULATION

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Summary

During the past several years there have been occasional, but recurring, reports of polyethylene telephone cable insulation embrittling and cracking in field service. This paper presents some correlations between our field experience and the laboratory test methods we designed to study this phenomenon. Environmental conditions that we postulated to occur in the field were applied, to determine their effects on insulation that has degraded. Effects of colorants and connectors used, and effects of the copper conductors are considered, also. Some comparisons are made between plastic types.

Introduction

Cable Features

The first polyethylene-insulated multipair telephone cables came into use in 1950. These cables were less subject to moisture-induced performance deterioration than were comparable paper-insulated cables, and, therefore, offered outstanding features where splices and drops necessitated many openings in the protective outer sheaths. Distribution terminals for polyethylene-insulated cables did not require hermetic sealing, thus installation and operating costs offset the higher initial cost of the polyethylene insulation.

Polyethylenes Used

The first polyethylenes used for multipair telephone cable insulations were 0.92-density (low density) polymers with a melt index range of 1.0/1.6 gms/10 min. Use of these polymers was gradually phased out during the mid-1950's by 0.92-density polymers in the 0.2/0.4 melt index range. In early 1959, this usage of the 1.0 melt index polymers was discontinued. At the same time, the antioxidant content of the 0.3 melt index polymers was increased from 0.05% to 0.10% Santonox®. In mid-1962 Superior Cable Corporation (now Superior Continental Corporation) discontinued the use of 0.92-density polyethylenes and began using 0.95-density (high density) polyethylenes in the 0.2/0.5 melt index range, stabilized with 0.10% Santonox antioxidant.

Colorants Used

Prior to 1957, pair identification consisted of natural polyethylene paired with transparent red, blue and green; red was paired with orange or blue for tracer pairs. In 1957, the Western Electric Company introduced a set of 10 polyethylene color concentrate formulations which provided improved pair identification together with minimized differences in dielectric constants of insulations: all of these colorants, except black, contained titanium dioxide. The independent cable manufacturers began converting to this color scheme in 1957, and have essentially used the same colorants since.

Splicing Enclosures

Performance degradation observed to date has been limited to insulation, exposed to air within splicing enclosures, where the protective outer cable jacket has been removed for connecting. Lengths of uncovered insulation have extended, within enclosures, from the edges of tape wraps to wire connections, and insulation in these lengths has been subject to degradation.

The enclosures have been (1) aerial for cables supported above ground, and (2) pedestals that are "planted" in the earth at the lower end to receive ends of buried cables from underground. Aerial splicing closures are normally black, while pedestals are usually green (to blend with foliage) or galvanized iron. Air temperatures that have been developed within these enclosures throughout their broad range of geographical locations and varying year-to-year conditions have not been estimated by us; however, it must be assumed that enclosures located in southern areas develop higher average internal temperatures. It must also be assumed that air within pedestals, planted in the earth at the lower end and well sealed at the upper end, will accept moisture from the earth and develop high relative humidities with frequent condensation and wetting of insulation exposed within the enclosure. The opportunity for condensation is probably much less for aerial splice closures.

Degradation Reported

To date, six cases of embrittled and cracked polyethylene insulation have been reported to our laboratories. A typical failure is shown in Figure 1. Except for one report from southeast Iowa, all degradation has occurred in southern states, in cables manufactured during and after 1958. Table 1 summarizes the occurrences of embrittling reported to us; it includes local climatological data for average yearly temperatures for the respective nearest recording points, covering the in-service periods of the cables. In general,

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time to initiate degradation is inversely related to average temperature.

Specimens Analyzed

Specimens referred to us for analysis showed some or all of the following (some samples were too small for all these evaluations):

1. Degradation occurred only within splicing enclosures.
2. It occurred only outside the polyethylene sheath.
3. Most severe cracking occurred over bends and twists.
4. Insulations containing highest concentrations of titanium dioxide white colorant were most severely affected.
5. Oxidation of degraded insulation was severe, as measured by infrared absorbance at 5.81 microns (carbonyl).
6. Density of cracked insulation was high, compared to density of insulation contained within the polyethylene sheath.
7. Levels of antioxidant (as Santonox) were low in cracked insulation, compared to levels in insulation contained within the polyethylene sheath.

Most of these symptoms (and the geographical locations of the field reports) suggested the mechanism of failure to be thermally induced oxidation of the low-density polyethylenes used at that time. The degrading effects of thermal exposures and several other possible contributors were, therefore, studied in our laboratories.

Titanium Dioxide

Because insulations containing TiO_2 had invariably been most severely cracked, our first tests were constructed to gauge the effects of TiO_2 on the heat-aging characteristics of polyethylenes used in the 1958-1961 period. Insulation specimens were prepared using natural PE, and PE containing one to five times the amount of standard white color concentrate normally used. The six materials were extruded over 19-AWG bare soft copper conductor with a 0.013-inch coating of insulation. Familiar "pigtail" test specimens were made by wrapping the insulated conductor around itself 10 times in a tight helix.

The groups of six test specimens were then placed hanging within loosely closed glass jars, which were placed into forced convection ovens for heat aging. Tests were made at 10°C increments from 130°C to 70°C. "Time-to-fail" was defined by the first appearance of surface cracks, for specimens exposed to this uncirculated air at 90°, 80°, and 70°C. "Time-to-fail" was defined as the first appearance of green discoloration and the odor of carbonyl in specimens exposed at 130°, 120°, 110°, and 100°C. Uncirculated air testing was applied because it was thought the air within splicing closures was essentially uncirculating.

The results of these tests are presented in Table 2 and shown plotted in Figure 2 for white insulation. *The significance of these data lies in the extrapolation to greater time periods -- which indicates that low density polyethylene of 1.9 melt index, colored white by the addition of rutile TiO_2, will begin to crack in 10 to 12 years at 30°C.* It must be emphasized that these test specimens contained 0.04% Santonox as available antioxidant at the onset of testing, and that specimens containing lower concentrations than this would crack in shorter periods of time.

The data of Table 2 show the natural insulation to be more resistant to thermal degradation than the white insulation. The data also show that concentrations of TiO_2 above that normally used do not additionally deteriorate this insulation.

Still versus Moving Air

Because minor air currents must occur within splicing enclosures, a set of similar tests on white specimens were conducted within forced convection ovens by hanging the specimens directly in streams of rapidly moving air. The results of these tests are shown in Figure 3 compared to the uncirculated air data. They indicate that air currents would not significantly reduce the service life of this insulation in the service temperature range. They further indicate that the polymer degradation in service is not caused by loss of Santonox antioxidant by evaporation from the surface of the insulation into the air within the splicing closure.

High Humidity

Splicing closures for buried cables are open to the earth at the bottom, and where the aboveground sealing is effective, air within these closures should often attain a 100% relative humidity. The effect of such high-humidity conditions was studied by hanging sets of white specimens in tightly closed jars over water. The results of these tests show that the presence of moisture (probably because it limits the oxygen concentration) enhances the service life of polyethylene insulation. No degradation was observed for test periods well beyond those required to produce cracking in still and moving air, at the same test temperature. Although these laboratory tests indicate that high concentrations of moisture in the air are beneficial, some field experience does not. One inspection of pedestals revealed extensive cracking within one pedestal that was standing in water.

Service Life Predictions from Climatological Data

Laboratory oxidative aging data is usually taken under well defined and closely controlled temperature conditions. Data such as that shown plotted in Figure 2 is usually developed, one temperature at a time, until a curve can be drawn. The curve is then extrapolated to a mean temperature that is representative of the geographical area being considered. Thus, from the outset oxidative

stabilization is based on average temperatures.

However, field conditions represent a myriad of temperature profiles that depend on geographical location, local shading from sunshine, daily temperature swings, annual temperature swings and many other variables. Accurate local climatological data is available for locations well distributed over the United States and many other countries, but service life based on these mean temperatures is likely to be optimistic for two reasons: (1) temperatures in pedestals and closures are substantially higher than ambient due to direct solar exposure[1], and (2) the rate of degradation as a function of temperature is not linear.

From Figure 2, it can be seen that the experimental data predicts that service life will be halved with an 8°C temperature increase. Aging rate as a function of temperature change from a mean value is, therefore, represented by the relationship in Table 3.

Now consider, as an example, the air temperature inside a pedestal throughout an ambient daily temperature profile as shown in Figure 4.

Then combining aging rate factors from Table 3 and temperatures within a pedestal as related to the outside air mean temperature during one day from Figure 4, we derive the data of Table 4.

Thus, the degradative aging of insulation within the pedestal would be 57.6 hours relative to 24 hours at the daily mean temperature of t_0. Or an effective daily aging rate of $57.6 \div 24 = 2.4$ times that occurring at a constant level of t_0. Alternatively, it may be said that a correction of about +10°C should be added to the mean daily temperature to compensate for this effect.

Insulation installed in areas having small daily and seasonal variations in temperature would not be exposed to an acceleration factor as large as that calculated here. However, the factor of 2.4 calculated here appears typical for warm (and, therefore, most critical) climates. Application of this aging correction factor to the service life range presented in the previous section converts this 30- to 70-year range to a 12- to 30-year life, that is more consistent with field experience.

The day/night aging acceleration factor calculated above is intended to be used with the local average temperature to compute a number of aging hours relative to the 24 hours within one day. Similarly, a summer/winter aging factor exists that would be computed from mass seasonal temperature swings and the local yearly average, that would further reduce the anticipated service life: a summer/winter aging factor of 1.2 was calculated from climatological data in the south central Texas installation. However, an aging factor for the cloudy days in a location would be less than 1.0 and would have the compensating effect of extending the service life.

Quantity of Antioxidant

If the data of Figure 2 are extrapolated to the 50.5° to 68.4°F (10° to 20°C) yearly average temperatures presented in Table 1 for the case histories, field failures would be estimated to occur in the 30- to 70-year range; and applying the aging factor derived above, the expected service life is reduced to 12-30 years. However, a factor of 2 to 3 still exists between the calculated and the experienced service life.

A partial answer to this discrepancy may be the possibility of low antioxidant levels in the insulation at the time of installation. The insulation reported in the curve of Figure 2 contained 0.04% Santonox. At manufacture it might have contained 0.07% -- having lost 0.03% during extrusion (see Table 5). If this polyethylene had contained less than the 0.04% Santonox, it would have failed in shorter time periods throughout the testing represented by Figure 2.

Measurements of antioxidant concentrations* in insulation that has remained below ground and within the polyethylene sheath suggest that cables containing relatively low concentrations of antioxidant could have been installed. For example, insulation from within the sheath in the buried 19-AWG cable from Texas contained only 0.01% Santonox. Insulation from 22-AWG cable that had been inside the pedestal, within the sheath, in the central North Carolina project contained 0.03% Santonox. Insulation from within buried sheath of 24-AWG cable in eastern North Carolina contained 0.05% Santonox.

Effect of Insulation Thickness

Of the above, the degradation of the insulations from Texas and central North Carolina may be attributed to low Santonox concentrations. However, the premature degradation of the insulation from eastern North Carolina is surprising, because it contained about 0.05% Santonox in buried sections. A possible answer here lies in the differences in insulation thickness for the three cables. Work done in our laboratory shows that thin-wall insulations degrade and crack faster than thicker coatings of the same polyethylene. Degradation, as indicated by the appearance of green discoloration, begins at the copper/insulation interface and progresses radially outward toward the outer surface. Therefore, it can be accepted that 24-AWG insulation containing 0.05% Santonox can degrade in approximately the same time period as 22-AWG insulation containing 0.03% and 19-AWG insulation containing 0.01% Santonox.

Effect of Copper Substrate

A series of accelerated aging tests was made in air to gauge the effect of copper substrate on the

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**All measurements of antioxidant concentration reported here were determined by the ultraviolet method which determines the quantity of unspent Santonox. We have assumed that little antioxidant has been consumed within insulation that has remained buried within the ground during its service life.*

service life of a low-density polyethylene insulation stabilized with 0.1% Santonox and containing 1.0% rutile titanium dioxide. The same insulation thickness was used throughout. The hollow insulation was obtained by removing the 22-AWG copper conductor from within the insulation before heat aging.

The data in Table 5 show that copper accelerates the reduction of Santonox antioxidant in this low-density polyethylene insulation. This insulation on copper conductor lost over 10 times the quantity of antioxidant during heat aging than did the same insulation heat aged in contact with aluminum conductor. The same insulation on tinned copper lost slightly more than it did on aluminum. The hollow insulation probably lost as much antioxidant as it did due to contact with unremoved copper dust during heat aging. Oxygen uptake tests[2] shown in the last column, show also the extreme degradative effect of the copper conductor, compared to aluminum.

The Effect of Water

In a previous section it was concluded that moisture as a gaseous component in air, normally found within splicing pedestals, did not reduce the service life of low-density polyethylene -- in fact, it extended the life. However, during falling temperatures of evening and night, condensation of gaseous moisture occurs within many splicing closures; this condensed water runs down exposed insulation and may itself remove antioxidant.

That water washing does indeed remove Santonox is shown by Table 6. The insulations were two of those described in the previous section. Immersions were made with insulation on conductors.

Because no oxygen was available for oxidation in these tests, the reductions in Santonox concentrations appear to have been caused by extraction by water. The losses for both samples were approximately the same, which indicates a different mechanism from that associated with oxidation in the previous section.

It is, therefore, likely that intermittent washing by water droplets within splicing enclosures has additionally reduced the service life of low-density polyethylene insulations.

The Effect of Silicone Grease

Cracked insulation observed in splicing closures has been in the vicinity of (1) crimp-type connectors, or (2) plastic tubes used to cover twisted and soldered joints: all of these units have been filled with silicone grease. It is, therefore, logical to suspect that silicone grease is a cracking agent for low-density polyethylene, or that it is capable of extracting Santonox and leaving the insulation without protection against oxidation.

We evaluated the effect of silicone grease by testing wrapped specimens of the same materials reported in Table 2. After wrapping, the specimens were smeared with thin layers of silicone grease over the coils and then heat aged at 70°C in still dry air and still moist air. No cracking occurred in either condition up to 230 days on test (when the tests were discontinued); whereas, cracking did occur in about 200 days for all uncoated white specimens tested in still dry air at the same temperature.

We, therefore, concluded that thin coatings of silicone grease did not reduce the service life of this insulation -- in fact, the coatings appeared to extend the service life.

Molecular Weight

Between 1957 and 1960, most telephone cable manufacturers upgraded their polyethylene insulation from 0.92 density, 1.3 melt index to 0.92 density, 0.3 melt index types. This increase in molecular weight did provide improvements in mechanical properties, but did little to increase the service life of insulation exposed to warm air and condensed moisture within splice closures.

Laboratory testing of white 0.3 and 1.3 melt index insulations on copper conductors shows little difference in "time-to-crack" for twisted specimens heat aged at 96°C. Insulations that developed cracking in the field were found to have been made from both 0.3 and 1.3 melt index polyethylenes. Curiously, one installation contained a mixture of both types, and cracking was essentially the same for both materials. Although tests to measure rates of thermal degradation in natural polyethylenes may favor higher molecular weight polymers, the combined effects of the TiO_2 colorant, the copper substrate, and water on both polymers swamp the advantages offered by increasing molecular weight. Add to these factors varying antioxidant content and the many in-service environmental factors and the subject becomes very complex.

High Density Polyethylene

The first reports of in-service cracking of polyethylene insulation caused our laboratories to initiate a study to determine the nature of the cracking problem. Our second objective was to determine the comparative performance of high-density polyethylene insulation, because we had supplied cables based upon high-density polyethylene since 1962.

Tests completed to date indicate that high-density polyethylene insulation will not crack as readily as low-density insulation when exposed to air within splicing closures. In fact, high-density insulation appears to offer several times the service life offered by low-density insulation under these conditions.

The longer service life offered by high-density polyethylene appears to be associated with its higher degree of crystallinity, which limits the rate of oxygen permeation to the insulation/conduc-

tor interface -- the site of the initiation of degradation. Oxygen uptake tests at 140°C (where both products are molten) show only slightly superior stability for white HDPE insulation on copper conductor, compared to LDPE. However, laboratory tests, designed to predict service life (such as presented in Figure 2), all favor high-density polyethylene where similar concentrations of Santonox antioxidant are considered.

Studies to determine optimum stabilization for high-density polyethylene insulation have been in progress in our laboratories, but we believe this work to be a subject separate from that being reported here.

Conclusions

We conclude from the above that the embrittlement of polyethylene telephone cable insulation observed to occur within splicing closures has been caused by oxidation, at the elevated temperatures existing within the closures. The oxidative process has been accelerated by the presence of titanium dioxide colorant within the insulation, and by water from condensed internal moisture washing away antioxidant. Antioxidant did not evaporate in significant amounts in these installations; it was consumed during oxidation of polyethylene that was accelerated by the presence of copper conductor and titanium dioxide colorant.

Degraded insulation examined appears to have contained low concentrations of antioxidant when placed into service. Such insulation failed at shortest service periods in areas of highest temperatures. Insulation that remained buried did not degrade, due to lower temperatures and the presence of high humidities.

High-density polyethylene insulation appears to offer longer service life under the same conditions of environment and stabilization.

In general, accelerated aging tests made at high temperatures must be interpreted with caution. Tests made above the melting temperatures of crystalline polymers may not correlate with results obtained at service temperatures. We suggest testing over temperature ranges that enable extrapolation to service conditions.

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2. W. L. Hawkins, R. H. Hansen, W. Matreyek and F. H. Winslow, "The Effect of Carbon Black on Thermal Antioxidants for Polyethylene," *Journal of Applied Polymer Science*, vol. 1, issue 1, pp. 37-42, 1959.

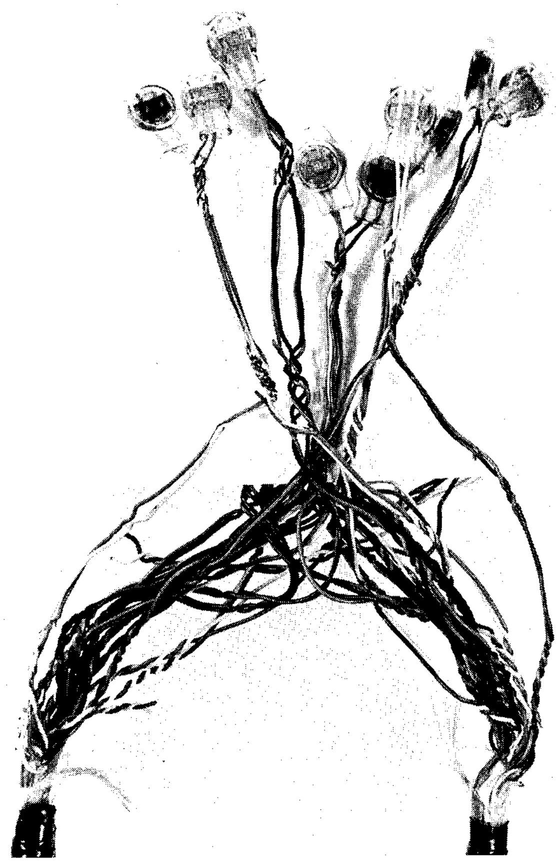

FIGURE 1

In-Service Degradation of Polyethylene Insulation

FIGURE 2

Test Temperature *versus* Time-To-Fail - In Still Air

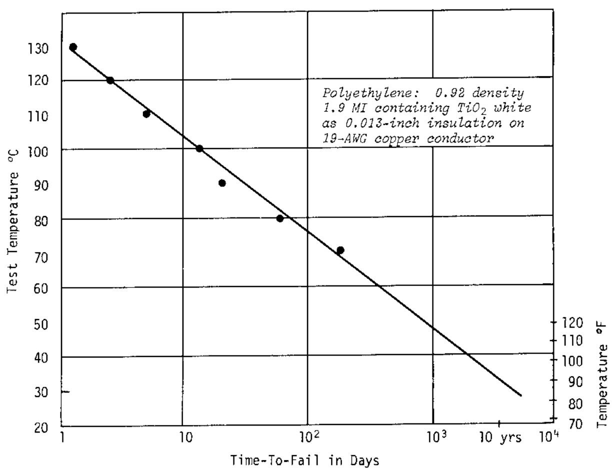

FIGURE 3

Test Temperature *versus* Time-To-Fail - In Moving Air

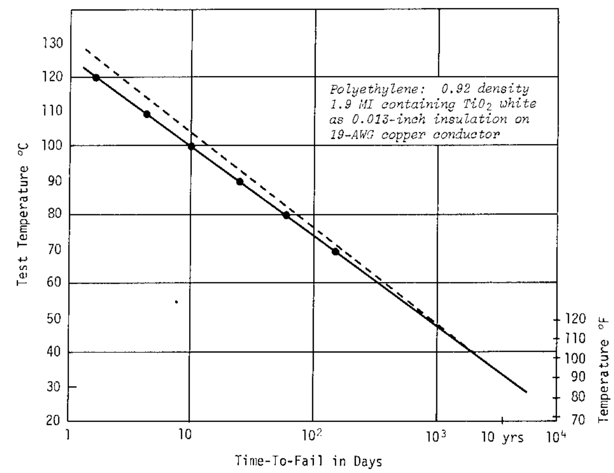

FIGURE 4

Approximated Daily Temperature Variations in Ambient Air and in Air within a Splicing Closure - Compared to the Yearly Mean Temperature

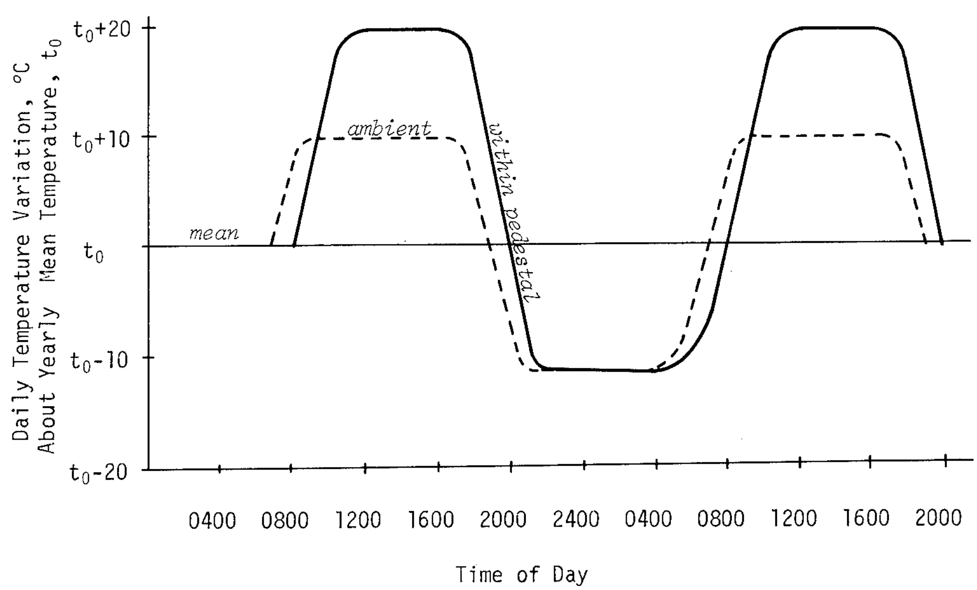

TABLE 1

Data Relating to Reported Insulation Failures

Location	Cable Installed	Cracking Reported	Years to Degrade	Average Temp °F	Conductor Gauge
Eastern North Carolina	1958	1967	9	60.0	19
Eastern North Carolina	1959	1967	8	60.0	24
West Central Virginia*	1959	1969	10	52.9	19
Southeastern Iowa	1959	1968	9	50.5	19
South Central Texas	1960	1966	6	68.4	19
Central North Carolina	1961	1971	10	58.0	22

*Cracking occurred in aerial splice case; others occurred in pedestals.

TABLE 2

Time-to-fail in uncirculated air for natural and white polyethylene(1) insulation(2) over 19-AWG copper conductor.

Temperature (°C)	Time-To-Fail In Days					
	NAT	IX(3)	2X	3X	4X	5X
130		1.25				
120		2.60				
110		5.50				
100	Over 26(4)	15	14	13	13	13
90	Over 29(4)	18	18	21	21	21
80	Over 78(4)	59	71	78	71	74
70	Over 230(4)	192	192	217	217	192

(1) 0.918 density, 1.9 melt index

(2) Insulation thickness 0.013 inch

(3) X represents the normal concentration of white masterbatch

(4) No failures observed. Tests discontinued at times shown.

TABLE 3

Aging Rate Factors from Data Plotted in Figure 1

Temperature Difference from the Mean (°C)	Aging Rate Factor
+16	4.0
+12	3.0
+ 8	2.0
+ 4	1.5
0	1.0
- 4	0.7
- 8	0.5
-12	0.33
-16	0.25

TABLE 4

Calculation of Degradative Aging Relative to Mean Daily Temperature

Time	Temperature(°C) Within Pedestal	Aging Rate Factor	Duration(hrs)	Relative Aging
0800	t_o			
1000	t_o+16	2.0	2	4
1200	t_o+20	5.0	2	10
1600	t_o+20	6.0	4	24
1800	t_o+16	5.0	2	10
2000	t_o	2.0	2	4
2200	t_o-12	0.6	2	1.2
0400	t_o-12	0.33	6	2.0
0800	t_o	0.6	4	2.4
			24	57.6

TABLE 5

Effect of Conductor Type on Consumption of Santonox Antioxidant in LDPE Insulation

Sample	% A/O as Received	% A/O After 24 hrs @ 125°C	Hours to Absorb 10 ml O_2/gm @ 140°C
Uncolored Pellets	0.100	-	-
Insulation on 22-AWG Copper	0.071	0.026	5.5
Insulation on 22-AWG Aluminum	0.069	0.065	120.5
Insulation on 22-AWG Tinned Copper	0.066	0.060	15.0
Hollow Insulation	0.071	0.061	60.0

TABLE 6

Effect of Water Immersion on Concentration of Santonox Antioxidant in LDPE Insulation

	Percent Santonox Antioxidant		
Sample	Original	After 3 days in H_2O at R.T.	After 3 hours in Boiling H_2O
Insulation on 22-AWG Copper	0.071	0.067	0.045
Insulation on 22-AWG Aluminum	0.069	0.065	0.046

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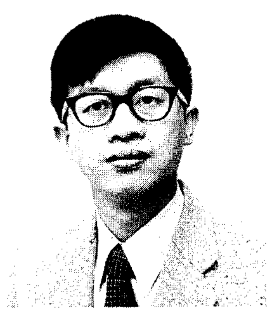
He has attended these symposia yearly since 1961, and has presented two papers prior to the present one. He holds a number of patents, mainly in the field of communications. He is a member of the Tau Beta Pi and Pi Tau Sigma honorary engineering societies and the Virginia/Carolinas section of the Society of Plastics Engineers.



Ming T. Chen, a native of Taipei, was educated in Taiwan, where he received his B.S. degree in Chemistry from Tanghai University.

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In 1956, he became associated with Superior Cable Corporation in Hickory, N. C., as a laboratory technician, advancing to R & D Engineer, to Director of Research and Quality Control, and to Director of Research and Engineering for Superior Continental Corporation.

In January 1969, Mr. Roberts was elected a company officer as Vice President, Research and Engineering, and in May 1970, to the Board of Directors of the company.

A member of the Institute of Electrical and Electronics Engineers, the Society of Plastics Engineers, the American Society for Testing and Materials, and the Society of Motion Picture and Television Engineers, Mr. Roberts is currently serving on the advisory board of the National Cable Television Institute. He holds a number of patents in the field of communication technology and has authored numerous technical papers for the AIEE, NCTA, IEEE, U. S. Army Signal Corps, and communications trade journals.

LONG TERM STABILITY OF POLYETHYLENE INSULATED FULLY-FILLED TELEPHONE DISTRIBUTION CABLES

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SUMMARY

Further results are reported of investigations into long term stability of polyethylene-insulated fully-filled telephone distribution cables. These include tests on cables subjected to temperature cycling and on water-immersed cables with severely damaged sheath. Ageing resistance of specially stabilised insulation based on different polyolefines is discussed. Where an increased margin of safety may have been required for very severe conditions of service, it has been obtained by improved stabilisation of polyethylene.

INTRODUCTION

The fully-filled cable has been described and extensively discussed at the three preceding symposia.[1-5] It became evident from these discussions, and from the papers published, that while the advantages of the fully-filled cable were already generally accepted, there was a requirement for more information on its long-term behaviour under very severe conditions of service. It was thought that more experimental data were required where the confidence was still based partially on a theoretical argument (e.g. that the electrical properties would remain stable on thermal cycling). Further experimental evidence was also required on certain aspects of resistance to ageing, which depend on the selection of the insulation and the filling compounds.

INTEGRITY OF INSULATION

The first condition which must be satisfied in selecting the insulation and the filling compound is that the insulation does not crack, and that it retains the necessary mechanical properties after contact with the filling compound (at the temperatures arising during the cable manufacture and service). This condition of compatibility can be satisfied by a number of combinations involving selected grades of low, intermediate and high density polyethylene, polypropylene and certain co-polymers, in conjunction with selected grades of petroleum jelly compounds, polyethylene/petrolatum mixtures, polybutene compounds etc. Each insulation/filling compound combination must be individually tested (e.g. as described in ref. 5), because many grades of the above materials give incompatible combinations.

The second condition, apparently more difficult to satisfy, is that the insulation should not embrittle and crack due to oxidation. The risk of premature failure due to oxidation affects only the bare cores at cable joints and terminations, and is likely to occur at high service temperatures. Within the fully-filled cable itself the insulation is unlikely to oxidise because it is surrounded by the filling compound and there is very little oxygen present.

At cable joints and terminations it is essential that the bare insulated cores should benefit from protection derived from two sources:-

(i) adequate active stabiliser system incorporated into the insulation at the manufacturing stage and, if this gradually migrates into the filling compound, then

(ii) resistance to oxidation derived from contact with, and absorption of, the filling compound.

The first of these is essential because some cable terminations can be made shortly after the manufacture and before the insulation had been affected by a prolonged contact with the

filling compound. If the cable joint is made and the insulated cores exposed to air after a prolonged contact with the filling compound, the insulation may have become very highly susceptible to oxidation. The deleterious effect on insulation of most filling compounds may be due to high susceptibility to oxidation of the filling compound itself and to extraction by the filling compound of the antioxidant originally present in the polyethylene. In the case of certain filling compounds, which improve the resistance of polyethylene to ageing, the latter effect is more than compensated by absorption into the polymer of certain natural ingredients of the filling compound which act as oxidation inhibitors. It appears that compounds based on synthetics and highly refined ingredients do not have such beneficial effect.

IMPROVED STABILISATION

Results of accelerated tests on 24 AWG copper cores insulated with 8 mils of conventionally stabilised polyethylene were reported earlier. These cores were made to a specification requiring a higher level of antioxidant than that recommended at the time by polyethylene suppliers, and the resulting insulation was considered satisfactory for most applications, with a capability of surviving at least 12 000 hours at an average temperature of 60°C. Table I compares accelerated ageing test results on that insulation with the corresponding results on the improved insulation which has now been adopted commercially. It can be seen that the accelerated tests show at least four-fold improvement. Table II shows results obtained with several alternative stabilising systems.

It has been already shown that even lightly stabilised polyethylene insulation becomes more than adequate after prolonged immersion in selected petroleum jelly compounds. In most of these tests the cores were exposed to the petroleum jelly at 80°C, but similar improvement in stability has also been found in solid polyethylene insulation immersed in the same petroleum jelly at 23°C for more than two years. Table III indicates that the intermediate density polyethylene (polymer F) benefits no less than the low density polymer from contact with selected petroleum jelly compounds. The results in Table III also show that the enhanced stability of both solid and cellular insulation was well maintained in a more severe test under air flow conditions.

TABLE I

Resistance to Oxidation of Low Density Polyethylene Insulation Protected by Conventional and Improved Stabilisation Systems

(8 mil insulation on 24 AWG copper conductor)

Ageing Test Condition	Oxidation Induction Period (hours)	
	Conventional Stabiliser (X-1)	Improved Stabiliser (V-1)
Static Air, 105°C	280	2000+
Air Flow, 105°C	180	740

+ Test continues

TABLE II

Resistance to Oxidation of Solid Low Density Polyethylene Insulation

(7 mil white insulation E on 26 AWG copper wire)

Stabilisation System	Induction Period at 105°C (hours)	
	Air Flow	Static Air
W-2	490	1150
W-3	850+	2050+
V-1	740	2400+
W-1	900	2600+
V-3	1300+	1300+

+ Test continues

TABLE III

Improvement in Resistance to Oxidation of Polyethylene Insulation after Immersion in Selected Petroleum Jelly Compounds

Insulation Details	Exposure to Filling Compound at 80°C	Induction Period at 105°C (hours)	
		Static Air	Air Flow
8 mil solid A on 24 AWG copper	None 42 days in S 42 days in R	250 160 2160	180 1900+
30 mil solid A on 19 AWG copper	None 14 days in P or Q	700 8000+	
30 mil solid F on 19 AWG copper	None 14 days in Q or R	650 6300+	
8 mil cellular B on 24 AWG copper	None 14 days in S 42 says in R	380 190 4300+	350 1900+

\+ Test continues

Accelerated ageing tests with controlled air flow were carried out to simulate the conditions of natural ventilation expected to exist in certain types of termination boxes. The effect of a moderate flow of air over the insulated core (100 ml/minute, giving six changes of atmosphere per hour) was found to be highly significant: data in Table I and II show that the life of the "dry" insulation under these test conditions was reduced by a factor of two or more, depending on the stabilisation system used.

In some of the accelerated ageing tests, conditions were changed to explore whether the presence of water vapour affects resistance to ageing. In the tests so far carried out (Table IV) there has been no indication that the deterioration of polyethylene was significantly accelerated by the presence of water vapour.

TABLE IV

Effect of High Humidity on the Resistance to Oxidation of Solid Polyethylene Insulation

(7 mil white insulation E on 26 AWG copper wire)

Ageing Test Conditions	Oxidation Induction Period (hours)	
	Stabiliser V-2	Stabiliser X-1
At 105°C in static air	480	200
At 105°C in static air after immersion in water at 75°C for		
(a) 4 days	670	300
(b) 11 days	400	100
Humidity cycling test at 23°-105°C	1140*	340*
At 96°C and 75% relative humidity	1360+	400+

* Hours in the oven at 105°C

\+ Test continues

EFFECT OF PIGMENTS

When both the polymer with its stabilising system and the filling compound have been proved to be adequate, it is still necessary to ascertain the effect of the various pigment masterbatches to be used. Cases have been reported of quite large differences in the ageing resistance of different colour cores, with some pigments apparently having a large deleterious effect. Once the problem is known, however, it is possible to select from commercially available masterbatches a complete range of colours which is satisfactory in this respect.

Table V illustrates results recorded for four sets of recently manufactured cores.

TABLE V

Comparison of Resistance to Ageing of Pigmented Cores

Colour	Induction Period (hours) at 105°C in Static Air			
	7 mil solid Polymer A/X-1 on 26 AWG Copper	11 mil cellular Polymer D/Z-1 on 22 AWG Copper	20 mil solid Polymer A/X-1 on 19 AWG Copper	5 mil cellular Polymer F/X-5 on 24 AWG Aluminium
Blue	-	510-580	820-840	2570
Red	430-460	750-770	940-960	2600+
Purple	410-430	-	-	-
Green	510-530	410-430	820-840	2600+
Yellow	480-510	-	670-750	-
Grey	480-510	430-460	-	2600+
Brown	410-430	820-840	840-910	2600+
Black	-	840-910	-	2600+
Orange	410-430	510-580	510-580	2600+
White	270-320	510-580	1080	-

\+ Test continues

HIGH DENSITY POLYETHYLENES

Certain selected grades of high density polyethylene have satisfactory mechanical properties and good compatibility with petroleum jelly filling compounds (Tables VI and VII). Basically, there is little difference in time to the commencement of oxidation (i.e. induction period) between the low and high density polyethylene protected with similar stabiliser systems (this does not apply to certain types of high density polymer containing harmful polymerisation catalyst residues). The embrittlement of low density polyethylene insulation develops gradually after the onset of oxidation and cracking of the insulation on bending occurs only after a period of time, typically half as long as the induction period. However, in the case of high density polyethylene insulation, severe embrittlement and spontaneous cracking may take place immediately at the onset of oxidation at the end of the induction period. This difference in behaviour on ageing is illustrated in Table VIII. For this reason we have given preference to low and intermediate density polyethylenes.

POLYPROPYLENES

Tests on available commercial polypropylene compositions have shown still inadequate stability after exposure to filling compounds:they do not benefit from the use of the petroleum jelly compounds which effectively protect polyethylene. Since our last report, further progress has been made with experimental polypropylene formulations (Table IX). Promising performance of some of these formulations justifies further tests on insulated copper wire.

STABILITY OF ELECTRICAL PROPERTIES

There is no reason to suppose that the cellular polyethylene/petroleum jelly system is unstable, but if it were unstable, then the most likely conditions under which the compound would tend to fill the cells would be those of temperature cycling. An experiment was accordingly carried out, in which a cable was subjected to 18 weekly temperature cycles, during each of which it remained for three days at 1°C and for three days at 50°C. For this experiment, a 100 pair cable was used, with 24 AWG aluminium conductors covered with 7 mils of cellular polyethylene. The cable contained a paper wrap followed by a Glover barrier* and extruded polyethylene sheath (the design normally used in the UK distribution network omits the Glover barrier). The cable was not subjected to any conditioning prior to the experiment. Table X shows that no important change in either the mutual capacitance (C_m) at 1 kHz, or the associated loss tangent, has occurred as a result of the weekly temperature cycles. Table XI shows similar evidence from measurements at 1 MHz on the same cable subjected to 48 daily temperature cycles between 1° and 50°C.

* i.e. aluminium/polyethylene laminate

TABLE VI

Effect of Immersion in Filling Compounds on the Tensile Properties of Higher Density Polyethylene Insulation

Insulation	Period of Immersion in Filling Compound at 80°C	Yield Stress (lb/in^2)	Break Stress (lb/in^2)	Elongation at Break (%)
Polymer F	None	1800	3250	660
(30 mil on 19 AWG copper)	14 days in P	2200	2300	570
	14 days in Q	2350	2250	620
	14 days in R	2300	2300	610
Polymer G	None	2850	5800	880
(8 mil on 24 AWG copper)	14 days in P	3400	4250	640
	14 days in Q	3150	3400	540

Note: Rate of extension 500% per minute

TABLE VII

Performance of Higher Density Polyethylenes in "Wrap Test"

30 mil Radial Insulation on 19 AWG Copper Conductor	Density (g/cm^3)	Test Temperature (°C)	"Wrap Test" after 14 Days Immersion Period and Subsequent Exposure for 12 Months at Test Temperature		
			Compound P	Compound Q	Compound R
Polymer F	0.932	80	Pass	Pass	Pass
		85	NT	Pass	Fail
Polymer H	0.950	80	Pass	Pass	Pass
		85	NT	Pass	Fail
Polymer G	0.952	80	Fail	Pass	Pass
		85	NT	Pass	Pass

NT = not tested

TABLE VIII

Oxidation and Embrittlement of Low and High Density Solid Polyethylene Insulation on Copper Wire

Insulation Details	Induction Period (Time to the Onset of Oxidation) at 105°C (hours)	Time to Embrittlement at 105°C (hours)
7 mil polymer A/X-1 (d = 0.918) on 26 AWG	200	290**
7 mil polymer E/W-2 (d= 0.927) on 26 AWG	1150	1450+
8 mil polymer A/X-1 (d = 0.918) on 24 AWG		
(a) after immersion* in P	1800	2700+
(b) after immersion* in Q	1450	3000+
10 mil polymer G/Y-2 (d = 0.952) on 22 AWG		
(a) after immersion* in P	1550	1550
(b) after immersion* in Q	1600	1600

* After 14 days immersion at 80°C

** Cracking only on severe flexing

\+ Test continues

TABLE IX

Resistance to Oxidation of Polypropylene Copolymer Compounds after Immersion in Filling Compound Q at 80°C

(20 mil thick sheet)

Stabilisation System	Time to Embrittlement in Air at 143°C (hours)	
	As Moulded	After 127 days in Q
M	1250	30
M + copper*	50	< 5
N	1500	280
N + copper*	900	10
N/1	1800	670
N/1 + copper*	1620	150
N/2	2250	1430
N/2 + copper*	1000+	380
O/1**	1500	1000
O/1**+ copper*	1300	900

* 0.1% fine copper dust incorporated in the sheet

** Black

\+ Test continues

TABLE X

Effect of Weekly Temperature Cycling Between 1° and 50°C on the Electrical Characteristics at 1 kHz

Pair Position	Control		After 18 Weekly Cycles	
	C_m (nF/km)	$\tan\delta_m \times 10^4$	C_m (nF/km)	$\tan\delta_m \times 10^4$
Outer Layer	63	46	63	57
2nd Layer	64	6	62	11
3rd Layer	63	7	62	7
4th Layer	64	6	65	6
5th Layer	63	6	64	6
Centre Pair	65	7	63	7

TABLE XI

Effect of Daily Temperature Cycling Between 1° and 50°C on the Electrical Characteristics at 1 MHz

Pair Position	Control		After 48 Daily Cycles	
	C_m (nF/km)	$\tan\delta_m \times 10^4$	C_m (nF/km)	$\tan\delta_m \times 10^4$
Outer Layer	64	29	62	25
2nd Layer	65	22	64	19
3rd Layer	67	22	64	20
4th Layer	64	23	65	20
5th Layer	65	21	64	20
Centre Pair	65	22	64	17

EFFECT OF SHEATH DAMAGE

This test was carried out to assess the effect of water entering the cable as a result of very extensive sheath damage. Twenty foot long samples of two fully-filled cables were immersed in water after the polyethylene sheath had been perforated with 24 equidistant holes (quarter inch diameter) helically located along the cable. In one case (a 100 pair cable with 24 AWG aluminium conductor, 7 mil cellular insulation with a paper core wrap) the holes were made through the sheath only, whilst in the other case (a 37 pair cable with 19 AWG copper conductor, 20 mil solid insulation with both paper and plastic laminate core wraps) both the sheath and wraps were penetrated to allow water direct access to the filling compound. Table XII shows that, in both cases, a large increase in mutual capacitance occurred only in the outermost layer: in one case reaching 8% after 150 days immersion and in the other 10% after 250 days immersion. The effect of water on the loss tangent was also pronounced in the outermost layer and decreased towards the centre of the cable. This large effect of water on the outermost layer is probably due to

TABLE XII

Effect of Water Penetration on the Electrical Characteristics of Fully-filled Cables at 1 kHz

Pair Position	100 pair Cable with Sheath Damage only				37 Pair Cable with Sheath and Core Wrap Damage			
	Control[a]		After 150 days Immersion[b]		Control[a]		After 250 days Immersion[b]	
	C_m (nF/km)	$\tan\delta_m \times 10^4$	C_m (nF/km)	$\tan\delta_m \times 10^4$	C_m (nF/km)	$\tan\delta_m \times 10^4$	C_m (nF/km)	$\tan\delta_m \times 10^4$
Outer Layer	63	30	68	109	51	48	56	120
2nd Layer	65	7	66	39	52	4	52	20
3rd Layer	65	7	65	19	52	4	52	11
4th Layer	65	6	64	12	-	-	-	-
5th Layer	65	7	65	9	-	-	-	-
Centre Pair	66	9	65	9	52	4	52	9

Notes: a Cable as received after manufacture

b Cable immersed in water at 23°C

this layer being in contact with the water-absorbent paper wrap. The paper wrap performs a useful function in the cable construction, but it does affect the electrical properties of the outermost layer.

FURTHER WORK

The work on environmental effects is continuing and further conclusions may be reached when all the results are available. It is intended to publish these in full detail on a future occasion. Tests in progress include further measurements of the effect of water on cables with damaged sheath (different cable constructions) and long term stability of buried cables without Glover barrier.

CONCLUSIONS

1. A known deficiency of thin polyethylene insulation (especially on copper conductor) has been its low resistance to oxidation. This limitation has been overcome by filling the cables with selected grades of petroleum jelly and by incorporating more powerful stabilising systems. These two measures are shown to be very effective and secure adequately long life for insulation exposed to high service temperatures. Selection of suitable and compatible combinations of polyolefine insulation, antioxidant and filling compound is of critical importance. For insulation, the balance of advantages is found to be in favour of low density or intermediate density polyethylenes. The basic disadvantage of polypropylene insulation in fully-filled cables is low resistance to ageing: this is because its resistance to ageing does not benefit from contact with petroleum jellies.

2. Temperature cycling of a fully-filled cable with cellular polyethylene insulation has been found to have no important effect on the mutual capacitance. Prolonged immersion in water, of cable with severely damaged sheath does lead to some changes, but not to such a degree as to affect significantly normal telephone traffic in distribution cables.

ACKNOWLEDGMENTS

The authors wish to express their thanks to Dr. A.L. Williams, Director of Research and Engineering, British Insulated Callender's Cables Ltd., for permission to publish this work.

Due acknowledgment is made to many colleagues in the Laboratory involved in this work, to Mr. E.H. Reynolds for his guidance and encouragement and to many units of the BICC Group for their assistance.

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APPENDIX I

MATERIALS EXAMINED

TABLE A

Polyethylene Insulation

Code	Nominal Density (g/cm^3)	Melt Flow Index (g/10 mins)
A	0.918	0.15
B	0.935	1.0
D	0.927	1.4
E	0.927	0.3
F	0.932	0.3
G	0.952	0.3
H	0.950	0.4

TABLE B

Filling Compounds

Code	Drop Point (°C)		Composition
	IP-31	ASTM D-127 (IP-133)	
P	68	76	PJ of low wax content
Q	75	80	PJ of high wax content
R	83	-	PJ of high wax content
S	55	70	Polybutene with polyethylene and wax

TABLE C

Stabilisers

All the polyethylene stabilisers used in this work were commercially available proprietary materials and for this reason they are not identified in this paper. Their general description is as follows:

System	Description of additives
X-1	phenolic antioxidant I, nominal concentration 0.1%;
X-5	as above, but nominal concentration 0.15%;
Y-2	phenolic antioxidants II and III together with a peroxide deactivator, nominal concentration 0.15%;
Z-1	phenolic antioxidant III, nominal concentration 0.2%;
V-1	phenolic antioxidant I at a higher concentration;
V-2	phenolic antioxidant I with a copper inhibitor, concentration 0.15%;
V-3	as above, but at a higher concentration;
W-1	high molecular weight anti-oxidant IV with a copper inhibitor, concentration 0.15%;
W-2	antioxidant IV with a copper inhibitor and a peroxide deactivator, concentration 0.15%
W-3	as above, but at a higher concentration.

APPENDIX II

TEST METHODS

Ageing Test Procedures

(a) Test in static air at 105°C

Helical coils of insulated core 1½-2 inch in diameter were aged in air circulating ovens using a separate glass tube cell, loosely capped with aluminium foil, for each core sample.

(b) Test with air flow at 105°C

Coiled samples of core were aged in separate glass cells of 1 litre capacity maintained at the required temperature by immersion in the vapour of boiling n-butyl formate. Preheated air was continuously passed through each cell at a

controlled rate of 6000 ± 500 ml/hour.

(c) Test at 96°C in a high humidity atmosphere

Coiled samples of core were aged over a saturated solution of potassium chloride in sealed glass vessels giving an atmosphere of about 75% relative humidity (partial pressure of oxygen ca. 60 mm Hg, 100 ml oxygen/ml insulation).

(d) Test with humidity cycling

Conditions as in (a) except that the following daily cycle was used:- A measured quantity of water was placed in the tube below the sample. The tube was kept for two hours at room temperature and then replaced in an air oven at 105°C. While the water was present the recorded sample temperature rose gradually, reaching 105°C after 6 - 8 hours, when all the water had evaporated.

The first signs of oxidative deterioration of insulation were recorded in all cases. The values of induction period quoted were recorded as time to the onset of increase in weight (about 0.5% W/W). Evidence of some form of physical deterioration was observed soon after: this could be either spontaneous cracking (in the case of high density polyethylenes), or cracking on twisting, or on twisting and re-exposure to 70°C. The onset of oxidation was also evidenced by a rapid increase in the dielectric loss (e.g. at 1 MHz) which occurred simultaneously with the weight increase.

Electrical Measurements

At 1 kHz measurements were carried out on 20 ft lengths of cable wound into coils of about 2.5 ft diameter. A copper tape was wound around the coil to provide an electrostatic screen. The core-to-core capacitance (C_{12}) of an individual pair was measured using a 3-terminal bridge and the core-to-ground capacitance (C_g) was measured using a 2-terminal bridge. In both cases all other cores and the external screen were connected to earth. Measurements were carried out at an applied voltage not exceeding 20 V.

At 1 MHz measurements were carried out on a 9 ft length of cable in the form of a coil 2.5 ft in diameter. Capacitance and loss tangent were measured using a 2-terminal Hartshorn and Ward dielectric test set.

The mutual capacitance (C_m) and the associated loss tangent ($\tan \delta_m$) were calculated as follows:-

$$C_m = C_{12} + \frac{C_g}{2} \qquad (1)$$

$$\tan \delta_m = \frac{C_{12} \tan \delta_{12} + \frac{C_g}{2} \tan \delta_g}{C_m} \qquad (2)$$

Measurements of capacitance were reproducible to better than 1% and loss tangent to ± 0.0001 or 10% whichever was the greater. Measurements were made on at least half the number of pairs in each layer of the cable. The values of mutual capacitance and loss tangent in the tables are the arithmetic means for each layer.

Stefan Verne, born in 1928, qualified first in rubber technology and then in chemistry in 1951. Joined the Central Research and Engineering Division of BICC Ltd. in 1954, after obtaining an M.Sc. for research on dielectric properties of solutions. His entire professional career has been concerned with studies of synthetic materials and with their utilisation in power and communication cables. Head of Polymer Physics Section since 1956 and Head of Rubber and Plastics Department since 1966.

Robert T. Puckowski graduated from London University in 1954 and was awarded Ph.D. in organic chemistry in 1958. Joined CRED of BICC Ltd. in 1957 and in 1961 was appointed leader of the Plastics Section. Has been particularly concerned with degradation and stabilisation of polyolefines and pvc compounds.

Albert Pinching was born in 1939 and joined CRED of BICC Ltd. in 1958. He has worked on various aspects of polymer physics and the application of polymeric materials in cables and was appointed leader of the Plastics Section in 1969, He studied at Northampton College (London) and the National College of Rubber Technology and is a Graduate of the Plastics Institute.

AN ALL-ALUMINUM-CONDUCTORED TELEPHONE EXCHANGE

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In an effort to provide optimum telephone service to their subscribers, the operating telephone companies must constantly strive to keep abreast of new developments in products and methods of application to increase operational efficiency. One of the more challenging of these developments for future use is a cable with aluminum conductors.

In recent years, an increasing demand for copper coupled with its relative scarcity has widened the price spread relative to other metals. In the telephone industry, this price increase manifests itself most notably in the form of growing outside plant expenditures. Since a large share of outside plant material costs is derived from cable purchases, and a good percentage of cable costs can be attributed to conductor materials, one can see that there may be some economic advantage to be realized through the use of a less expensive conductor metal. Much research has been devoted to this end throughout the cable industry. We at Anaconda, for instance, experimented with various bi-metal laminates, aluminum, and even considered sodium in our search for a suitable conductor. It was found that aluminum is the best candidate as an alternate to copper. This decision was based on availability, compatibility with standard cable manufacturing processes, stability under various environmental conditions, conductivity and final product handleability.

After reviewing the possible economic advantages to be derived from the use of aluminum conductored communications cables and the future implications thereof, we found that a subsidiary of a major holding company was interested in a field trial. We felt such trials would be of great value in preparing ourselves, both from cable production and applications engineering standpoints, for the future demands of the industry. A joint venture was begun early in 1970. For the following eight months, each company worked in preparation for the job. The outside plant personnel from the telephone company and from Anaconda found splicing, loading and terminating accessories which were particularly applicable to aluminum and developed techniques for applying them. While telephone company engineering worked on system design, Anaconda provided a new alloy for the cable conductors which its mills learned to draw and insulate. During the last week of August, when production of the 200,000 feet of cable and service wire was completed and when we felt we were prepared for any contingency, job construction was begun.

The site chosen for this trial was Alger, Michigan, a community in the east-central part of the state. The Alger exchange was chosen because the entire system consists of about twenty miles of plant. Also, a forecast of increased service demand over the next few years indicated that the system was in need of a complete rebuild. At present, the system serves only 172 subscribers, but a large lakeside development is being constructed nearby and will require telephone service from the Alger exchange.

The cable construction chosen for the buried trial is totally filled, single jacketed, and has an eight mil aluminum shield. At this point, there are two questions that probably have arisen: first, shouldn't one take special precautions for moisture protection with single jacketed cable in the ground, and second, isn't there a good possibility of corrosion of the aluminum shield below grade? The answer on both counts is no. Totally Filled is synonymous with moisture proof, and even if the jacket is damaged during installation, the cable core is still protected against moisture entrance and migration. Furthermore, the cable shield is flooded on both sides with filling compound, which affords excellent corrosion protection. This filling material is the same non-hygroscopic petrolatum-polyethylene compound which is used to fill Anaconda's Totally Filled copper conductored cables. The conductors are 20 gauge aluminum alloy and are polypropylene insulated. The same cable construction was used throughout the system, from the 200 pair at the Central Office to the 2 pair buried service wire. This is the factor which makes this system truly unique; aluminum conductors are used from the tip cable at the main frame right out to the house protectors. (See Illustration 1)

The cable was directly buried for this system in soil conditions ranging from fine sand to very hard clay. A trailer mounted Ryan plow with a rigid blade was used to place the main cables at a depth of 30 inches. (See Illustration 2) A winch drawn lawn plow, which was used to minimize lawn restoration, placed the house drops at a depth of 18 inches. (See Illustration 3)

At no time during setup or plowing was it necessary to use special techniques or non-standard handling practices with this cable. Above ground cable appearances for service wire connection and loading were housed in Utility Products pedestals, and most of the reel-end splices were directly buried at cable depth. During the course of construction, we received many comments from the Harris McBurney construction crew with reference to handling this cable. The consensus of opinion was that the men would not have known they were using special cable had they not been told in advance. According to these people, the cable's handleability, flexibility and resistance to damage was at least equal to that of copper conductored cable. In fact, when pulling a pedestal loop from the plow chute by hand, one man commented that the light weight of the cable in relation to its size allowed for easier handling than standard cables. (See Illustration 4)

A possible disadvantage in using the aluminum conductored filled cable during the construction of a system could arise from the fact that the cable is considerably larger in diameter than standard buried cables. For instance, an unfilled 200 pair 22 gauge copper conductored cable designed for direct burial will have an overall diameter of 1.54 inches whereas the 200 pair equivalent used for the Alger job measured 2.14 inches. In a directly buried system, this size difference demands nothing more than a change of the plow chute or a one size increase in pedestals, neither of which is particularly difficult or costly. However, if any part of the system were being placed in ducts, this diameter increase could have a much greater economic effect, and could even make aluminum conductored cable unattractive.

The reasons for this diameter increase are rather straight-forward and simple: An aluminum conductor must be 26 percent larger in diameter than a copper conductor to achieve the same electrical resistance. And in the case of the 20 gauge conductor, this size increase dictates that we place 28 percent heavier insulation on the conductors in order to regain the cable's original .083 microfarad per mile mutual capacitance. Furthermore, when we replace the air in the cable interstices with the filling compound, a less perfect dielectric, we must again boost the insulating thickness by 24 percent to keep our mutual capacitance in line. The possible use of foamed insulation materials in the future could alleviate the need for such heavy insulation walls, which would bring cable diameters much closer to those with which we are accustomed to working.

A significant portion of our research time was spent on the selection of suitable accessories and the development of application techniques for our alternate metal. Although the Alger system is all 20 gauge conductored, we felt we should prepare ourselves for work with different sizes. This could have made the choice of accessories and application methods a bit difficult; for we had originally planned to use two different grades of aluminum for cable conductors. For the larger gauges we were planning to use electrical conductor grade metal which would have given us adequate conductivity but less than desirable handling characteristics. Then for the smaller gauge conductors we would have used a tougher alloy for handling and processing purposes, and in doing so would have lost the desired conductivity. Fortunately, the Anaconda research people alleviated many of the problems that could have arisen in this area before we field people even entered the picture. They accomplished this by providing an aluminum alloy for the Alger cable which must be considered a breakthrough in aluminum technology. This alloy displays some characteristics that, eighteen months ago, were not considered available in aluminum. For example, when compared to electrical conductor grade aluminum: the new alloy has greater tensile strength, several times greater elongation at break and less notch sensitivity with essentially the same conductivity. What this all means to us is that we now have a conductor with the cost figure of aluminum and with vastly improved handling characteristics.

In the splicing, loading and termination phase of the Alger job, we began looking closely at the peculiarities of aluminum and chose our methods and materials accordingly. The more prominent of the characteristics which influence the use of aluminum conductors will be discussed in the order in which we encountered them during our research work.

When preparing for installation of the Alger system, one of our prime objectives was the acquisition of high quality mechanical connectors for conductor splicing. The first phenomenon we had to consider when choosing connectors for jointing aluminum conductors was oxidation. When aluminum is exposed to air, a thin translucent oxide film begins to form on its surface almost immediately. This is both an asset and a liability to us when we consider use of aluminum for electrical conductors. The oxide film is extremely tough, and once it has formed it provides protection for the underlying aluminum against further oxidation or disintegration. On the other hand, this oxide is a very poor electrical conductor, which dictates that we use a connector whose contact elements pierce the

oxide layer and then remain firmly implanted against the aluminum beneath. Naturally, if there is any relaxation in the contact area there is a good possibility of oxidation of the aluminum at that point and a resulting high resistance joint.

The next peculiarity of aluminum which had to be dealt with was its notch sensitivity. The problem here is that an aluminum conductor will lose a greater degree of its workability and tensile strength when scored or notched than will copper under the same conditions. This characteristic forces us into a rather precarious position with respect to the choice of mechanical splice connectors. We now are required to use a connector that will penetrate deeply enough into the conductor to insure adequate oxide penetration and yet one which will not notch the conductor deeply enough to significantly reduce its physical strength.

There is another complicating factor which must not be overlooked when choosing connectors. When working with the aluminum equivalent of 22 gauge copper, one must be aware that he is actually working with 20 gauge metal. An attempt to use connectors designed for 22 gauge copper on the aluminum would certainly yield adequate oxide penetration and a large contact area, but the contact element of the connector would penetrate so deeply into the 20 gauge aluminum as to cause loss of physical strength.

Tensile strength is another parameter which may alter application techniques of aluminum conductored cables as opposed to copper ones. Electrical conductor grade aluminum of normal temper will have about 75 to 80 percent of the breaking strength of a copper conductor of equal resistance. This characteristic is of less significance than the others we have covered; but could require the use of greater care during the handling and splicing of aluminum conductors.

During the winter and spring prior to installation of the Alger job, Anaconda and telephone company personnel searched throughout the industry for mechanical connectors which would be in adequate supply and which would work within all the limitations cited above. The only other requirement we placed on the connectors to be chosen was that they be of the insulation piercing type. The polypropylene insulation on the aluminum conductors is a very tough material and stripping every conductor for splicing as would be required with some connectors was deemed overly time consuming and difficult.

At the beginning of the Alger job we were using several different connectors, but in the final analysis we found only one completely acceptable with respect to physical and electrical characteristics. This connector is called the UAL and is a revision of the standard UR connector from the 3M Company. A number of changes were made on the UR, the more important of which involved the contact elements themselves. The U-shaped opening in the contact element which actually contacts the conductor was opened up slightly in deference to the larger conductor size. Also, the element was electro-plated with a new metallic material which looks promising for future aluminum work. This coating material is highly conductive and extremely ductile, so it will flow tightly against the aluminum under crimping pressure. On future production runs, 3M also intends to enlarge the wire entrance ports of this connector to accommodate the increased diameter over dielectric of aluminum. (See Illustration 5)

During the actual splicing of the system, we varied the use of our connectors a good deal to acquire as much knowledge as possible about each under various environmental conditions. For instance, we made some pedestal splices with the UAL connectors and some with the other types of connectors, and made the same variations in connector use for our buried splices. In a few splices, both pedestal and buried, we used the different types of connectors side by side to get direct comparison data over an extended period of time. Our initial findings were that the connectors other than the UAL notched the conductor too deeply and caused a great reduction in conductor strength.

Some of the UAL connectors have been in the field for over a year now and appear to be doing very well, but obviously, time alone will give definitive results on connector success. However, a fact that should be brought to light is that the craftsmen were able to splice this cable as efficiently as copper conductored cable of comparable construction. The larger conductor size did not reduce handling efficiency at all. The craftsmen stated, in fact, that the softness of the aluminum conductors allowed for somewhat easier handling than they had experienced with standard cable conductors. (See Illustration 6)

When planning for the loading and termination phase of the Alger job, we faced still another characteristic of aluminum which could cause headaches if not recognized and allowed for. The characteristic referred to is aluminum's susceptibility to galvanic corrosion. This type of corrosion occurs when two dissimilar metals, widely separated in the galvanic

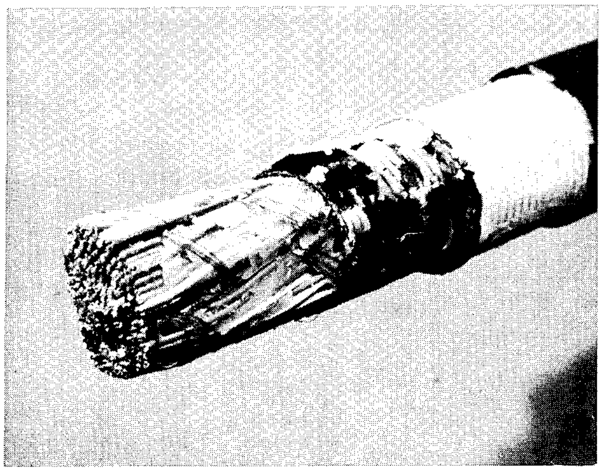


ILLUSTRATION 1. The aluminum cable used in Alger has a single jacket and an 8 mil aluminum shield. The cable is filled jacket to jacket with a moisture proof petrolatum-polyethylene compound.

ILLUSTRATION 2. The main cables were placed at a depth of 30 inches using a rigid type plow.

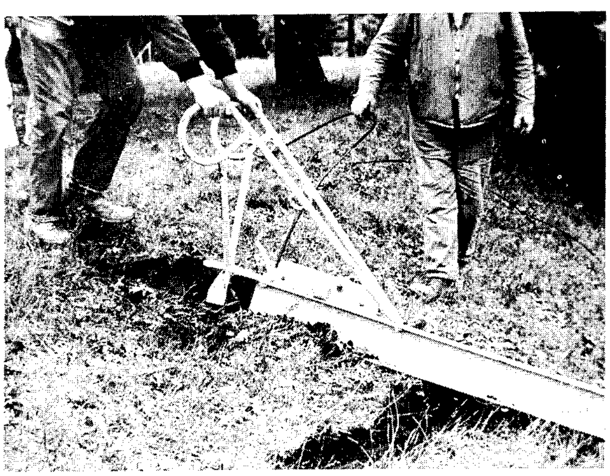


ILLUSTRATION 3. A winch drawn lawn plow was used to place service drops 18 inches down.

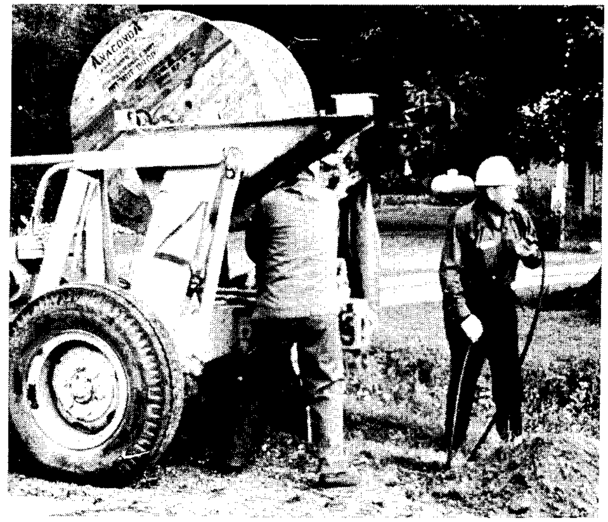


ILLUSTRATION 4. When the Harris-McBurney men pulled pedestal loops by hand, they commented that the cable's light weight in relation to its size allowed ease of handling.

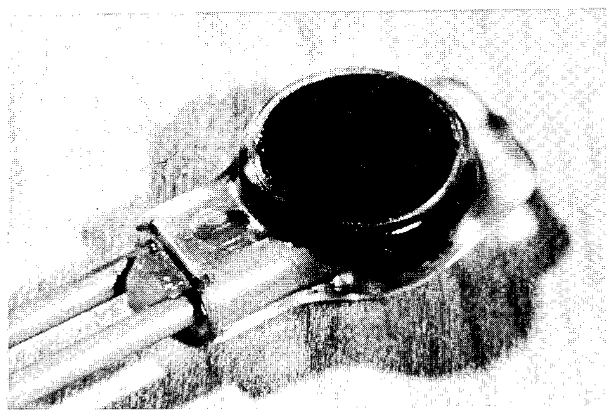


ILLUSTRATION 5. One type of mechanical connector used on the Alger job was the Skotchlok UAL from 3M.

ILLUSTRATION 6. An Anaconda Engineer completes a large pedestal splice using 3M's UAL connectors.

series, are placed in close proximity to one another in the presence of a conductive solution. Under these conditions, the metal which is higher in the galvanic series will be corroded. We will have, in essence, a low output battery. For example, when we have aluminum and copper together the copper will be cathodic, the aluminum will be anodic and will be rapidly eaten away. The key to beating this galvanic corrosion problem is keeping all joints between dissimilar metals moisture free.

On the Alger job, we encountered the jointing of dissimilar metals in three areas. There are aluminum-to-copper conductor splices in the Central Office and at the copper wound load coils. Also, we have an aluminum-to-brass interface between the aluminum conductored service wire and the lugs of the Cook Station Protectors.

The first of the three situations presented no particular difficulty, since the splice to the copper conductored tip cable was made and will remain in the relatively controlled environment of the Central Office. The other two interfaces which will be exposed to more extreme conditions were the basis of considerable research and development work. Coil Sales, Incorporated was chosen to supply the loading coils for the Alger system and with some assistance from Anaconda Engineering, eliminated the exposed copper-to-aluminum interface at the coils. They accomplished this by machine jointing the coil windings to twinned aluminum conductors and then potting the coil and the interface in a thermo-set plastic compound. As a result, the product that reached the field appears the same as a standard load coil, except it has aluminum leads. (See Illustration 7)

The danger of galvanic corrosion at the aluminum-to-brass interface in the station protectors was eliminated by a new product which was created by telephone company engineers and the people at Coil Sales. This new product is a lug, consisting of a brass spade into which a threaded aluminum stud is press-fitted. The aluminum-to-brass contact area is then encapsulated in a molded plastic block. Thus, we have a brass-to-brass connection at the protector and with the addition of an aluminum nut and washer, an aluminum-to-aluminum contact for the service wire. (See Illustrations 8 and 9)

Our final area of concentration centered upon splice closures and protection materials and techniques which were to be incorporated in the Alger job. We approached this task much in the same manner as the conductor splicing, using several different techniques in order to discern the most practical one.

Our fundamental approach to buried splice protection involved the hand packing of a compound into the splice bundle. This compound has basically the same component make-up as the cable filler. We worked on the theory that careful packing of this water proof compound would protect the splice from moisture, therefore, the only added requirement was some sort of case or sleeve to hold the material in place. (See Illustration 10) This concept proved itself worthy of use in Anaconda's Laboratories; however, when placed under field conditions and on a production basis, this method allowed several splices to get wet. After investigation of the difficulty, we found that the compound being used was too firm to lend itself to efficient craftsman use. In the majority of wet splices, it was discovered that the packing material had been applied liberally around the splice bundle but because of the firmness of the compound, had not been worked in among the connectors properly. Cold temperature, which has a hardening effect on the compound, seems to be the most prominent contributor to this improper packing. We found that by going to a softer compound, still with basically the same formulation, we were able to protect splices adequately. The GFC/REN Corporation is a supplier of this compound, and eventually plans to provide a hand packed arrangement with a removable polyurethane encapsulation over it. This concept could be interesting from an economic standpoint.

Although we have had to replace some splice closures because of moisture entrance, we fully intend to continue trying new and simpler methods of splice protection in the Alger system as they become available to us. The beautiful feature of this particular cable is that we are given a second chance at splice protection. Even though water may enter a splice, the filled core allows no moisture migration from that spot, thus limiting our trouble to a small, easily repaired area.

It is gratifying, and yet ironic that the only difficulty encountered in this system is one of adequate buried splice protection. Gratifying, in that none of our trouble can be attributed to the fact that this cable has aluminum instead of copper conductors, and ironic that in a telephone system which is ultra-modern and unique we were plagued by a problem as old as buried cable.

The all aluminum exchange in Alger was conceived as in information gathering and problem solving venture by the participating

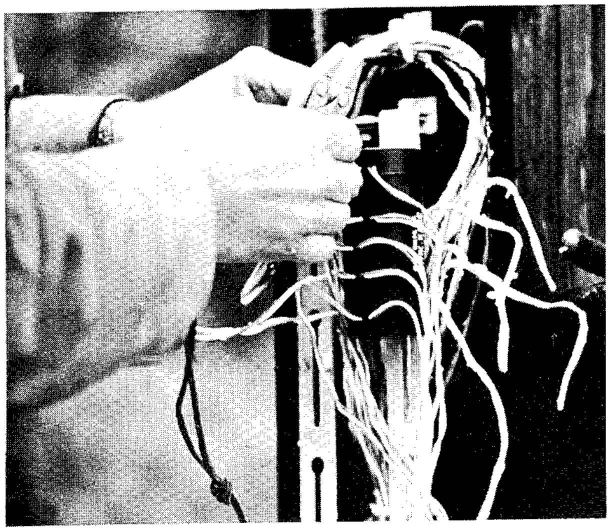


ILLUSTRATION 7. The load coils supplied by Coil Sales look like standard coils, except they have aluminum leads.

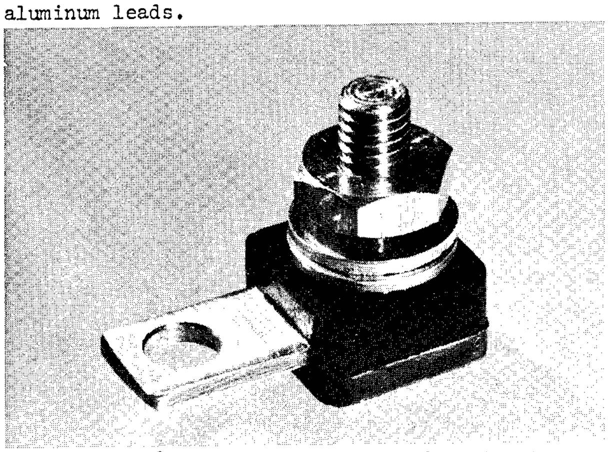


ILLUSTRATION 8. This brass to aluminum lug has interface encapsulated in a molded plastic block to prevent galvanic corrosion at the station protector.

ILLUSTRATION 9. An engineer completes a subscriber hook-up incorporating the brass to aluminum lug.

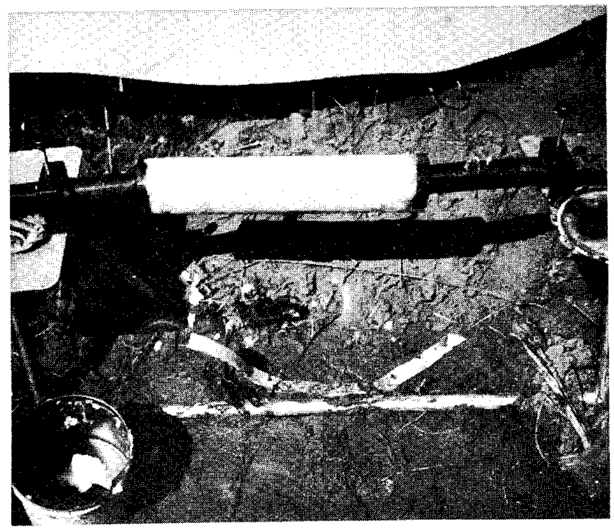
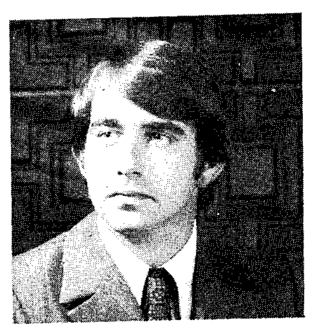


ILLUSTRATION 10. One of the first hand-packed splices awaiting direct burial.

companies, and as such, has been an eminent success. Moreover, we are confident that this system will provide high quality telephone service to its subscribers for years to come. The materials and techniques developed for the system and the vast working knowledge of the cable which we gained during the installation will be invaluable assets when the use of aluminum conductored communications cable becomes economically attractive to the industry.



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APPLICATION TECHNIQUES AND ACCESSORIES FOR FILLED COMMUNICATIONS CABLE

by

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Summary

With the advent of filled core multiconductor communications cables, a need has arisen to discuss installation techniques and accessories which are suitable for efficient and long lived field use. This paper presents considerations derived from laboratory study and actual inplant applications. Parameters of the filled core cable that require consideration are the compatability of the filling compound with accessories, handling characteristics of the compound while splicing, larger conductor insulation diameter and bending characteristics. The discussion and following conclusions are based on the Company's filled cable design which uses a petrolatum base compound for moisture protection.

Introduction

Operating telephone companies have faced the problem of moisture entering their cables ever since the switch was made from open wire to cable constructions. To help solve this problem, plastic insulated cables were developed. These did a good job and are still in service; however, moisture can still enter the cable core and cause severe problems on toll and carrier circuits. With the advent of filled cable, we prevent the migration of moisture in cables and thus have a reliable system which will last for many years. Filled core multi-conductor cables are not totally new; they have had military applications for a number of years. As far as telephone circuits go, Anaconda has had ALP-TF telephone cable installed for over two years and some interesting discoveries are worth mentioning.

The cable we are discussing is one that is totally filled with a petrolatum-polyethylene mixture. This compound completely fills the polypropylene insulated conductor core, is over and under the heat barrier tape and is over and under the shield. Thus, we have a totally filled cable. The cable shield is 8 mil aluminum and is coated on both sides with DuPont Zetabon.

For a filled cable system to be successful, the first and most important step is to discuss handling and splicing with the men who will be doing the work. Usually the craftsmen's initial reaction to the prospect of working with filled cable is that it is going to be a greasy mess and will cause them nothing but problems. If they are allowed to go to work without any preparation they work in a less than satisfactory manner without much regard as to the proper handling of the cable. For this reason we have found it quite necessary to discuss the cable and let the people work with it prior to actual inplant assembly. Once the men have a chance to work with the cable, they quickly change their attitude. Most of this attitude change takes place when they realize how the cable will help eliminate maintenance and repeated work. We must admit that we were quite skeptical about splicing and handling our filled cable when we first developed it; however after handling it at a wide range of temperatures we became convinced that our preconceived ideas were unfounded. We are not saying that filled cables do not present problems that are unique to this construction, but only that filled cables are not nearly as difficult to work with as one would believe.

To date, filled cable handling characteristics have been discussed with many people in the industry. These discussions have supported our own opinion of filled cable construction for all uses other than very high pair count feeders. This type cable is being successfully used in all types of applications from buried to aerial installations. This means that the cable operates satisfactorily over a temperature range from well below 0 to at least 150 F.

Our confidence in this cable construction is bolstered by the fact that many of the filled cables are being used for toll and trunk circuits. These lines would be recognized quickly as faulty if a problem existed. No problems attributable to the cable have been discovered. True, some problems did arise; but as with anything new, the unexpected happens. The problems that developed were due to direct buried splices. Here we had moisture entrance and as would be expected transmission problems. We found, however, that once the splices were opened and dried out or

replaced, the cable was still dry on each side of the splice. Once the leaky splices were re-worked and properly prepared, we had no further trouble in these areas. If we had been using standard PIC cables, the entire length or span would have been inoperable due to the water.

Making a filled core multi-conductored communication cable is not just a matter of taking a standard telephone cable and filling the core with a moisture protection compound. The electrical characteristics that are necessary for telephone use must be retained. This means that physical dimensions of the cable are enlarged and thus we have a different consideration to make when selecting accessory products for use with the cable. The addition of filling compound requires that we increase the conductor insulation to maintain mutual capcitance. Because we increase insulation thickness we make a larger core and consequently a larger diameter cable. These changes have little effect on most accessories; however, connector selection has to be modified due to the increased insulation. This increase is significant enough that most standard connectors will not work on all gauge sizes that they are designed for. Also we have to take into consideration the effects of the filling compound on accessories, as some materials are degraded.

Splicing

Field use has revealed that it is not necessary to clean the filling compound from the core prior to splicing. In fact, it is almost impossible to remove enough of the filling compound from the conductors to make a significant difference unless a strong solvent is used.

Cleaning gains no time in splicing as the operation increases splicing time much more than splicing with coated conductors. Splicing time for a man who has just become accustomed to working with this type of cable is only increased by 15%. After some time has been spent splicing, the man can cut his time down to almost the same period as he would use for a standard non-filled cable. One of the reasons that splicing time can be reduced back to a more normal time is because of the filling compound. The compound has a quite tenacious grip to the conductors and this grip helps to keep tip and ring conductors of a pair together. In a normal cable, the splicer will usually locate the long lay pairs, if not all the pairs, and twist the conductors together so that he does not split a pair during splicing. This procedure is used because it takes much longer to locate one conductor that has been lost than to eliminate the possibility. Filled cable has conductors that stay together almost no matter how roughly the core is treated. Another advantage is that the filling compound allows for quick group identification because the binders can be slid back to the cable butt where they will stay in place. Unlike standard cables, the filled cables do not require markers for the groups. The binders of standard cables must be tied off if they are to be used for identification.

Splicing of filled cables is much the same as splicing of non-filled cables. Currently most conductor joints are made with mechanical connectors; however, twisting and soldering is sometimes used. Several types of connectors are being used which are designed to connect the standard telephone wire gauges. These connectors do not all accept the increased insulation diameters of filled cable. Insulation diameters will be found in Table I. Wire entrance ports of connectors will be found in Table II. Connectors suitable for use with the Company's filled cable will be found in Table III.

TABLE I

INSULATED CONDUCTOR DIAMETER (INCHES)

CONDUCTOR SIZE AWG	STANDARD CORE	FILLED CORE
19	.062	.075
22	.045	.053
24	.035	.0425
26	.028	.035

TABLE II

CONNECTOR WIRE PORTS

CONNECTOR TYPE	PORT SIZE (INCHES)
B	.052
UR	.068
UG	.068
UY	.062
UAL	.082 .074 .082
MS[2]	.054

TABLE III

SPLICE CONNECTORS

AWG Size	Connector W/Stripped Insulation	Connector W/O Stripped Insulation
19	B, UR, UG	Picabond, UAL
22	B	UR, UG, UY, UAL, MS * and Picabond
24	—	All Except UAL
26	—	All Except UAL

* The cut-off tails are hard to remove, as all insulation is not cut through.

MANUFACTURING INFORMATION

Manufacturer	Material
3M Company	UR, UG, UY and UAL (Connectors) MS (Splicing Module)
AMP Inc.	Picabond® (Connector)
Several Licensed by Western Electric	B (Connector)

There are times when splicing is slowed appreciably. For example, when working in loose soil or sand, fumbling tools can be quite a problem. Sand and dirt mixed with the filling compound make tools difficult to use. To help reduce these occurrences, we found it helpful to attach leather bails to crimping tools so that they could be hung from the wrist. These wrist straps also aid in holding the tools when crimping, as they become increasingly difficult to grasp as they accumulate filling compound. The other tool used a considerable amount of time, the snips, is generally left on a finger and thus is always relatively easy to grasp. The accumulation of dirt and sand is the most disadvantageous aspect of splicing filled cable. We have found it quite handy to have a paper towel to lay tools on while they are not in use.

The filling compound is quite stable at working temperatures and we found that this stability is advantageous to the splicer. A man can easily splice a cable and not transfer the filler to his clothing. Because the compound is stable at skin temperature, it sticks to the hands and acts as an adhesive when connectors are picked up during splicing. The craftsman soon learns to gently pick up connectors, as contact with others in the container usually results in several being removed at one time.

Shield bonding presents no new problems. In fact, the filling compound aids in obtaining a more conductive contact. The shield is completely covered with filling compound, so when contact is made it is through the filler which helps keep oxygen and moisture out. Thus, there is less chance of oxidation or electrolysis, a common reason for bond failure on aluminum shielded cable.

Another asset is hand protection. At first our thoughts were that the filling compound would make the hands chill faster than normal at cold temperatures. This proved to be a false presumption because the compound holds in body moisture and prevents the chill effect of cool air moving across the skin. The compound also helps to prevent chapping. However, the splicer must be conscious of the cable filler on his hands as it is transferred to everything he touches.

When a splice is finished, it is a good idea to clean all tools before beginning another. Kerosene is in common use to loosen the filling compound from tools. It is a good choice as it is less flammable and harmful to people than many of the other solvents and because it leaves a slight oil on tools for their protection. Other organic solvents are quicker acting, however, they are quite flammable and not readily available to the operating company.

<u>Splicing: Step-By-Step</u>

1. Ring the jacket far enough back so that sufficient cable length will be exposed to allow for the type of splicing being used. Usually this will be about 18 inches. Slit the jacket from the ringed mark to the cable end.

2. Pull the jacket towards the end of the cable, it will easily slip off.

3. Mark the shield with a knife and turn it at the jacket end tearing it away. The knife cut will create a notch which will easily allow the shield to be torn.

4. Snip the binder over the core tape so that it may be pulled from the cable. This is done most easily by holding the cable where it has been rung, pulling the binder towards the end of the cable in a circular motion. That is, with the pulling hand going around the cable.

5. The core tape can then be removed by snipping it near the cable jacket.

Once the core is exposed, it will be to the splicers advantage to be ready for anything he plans on doing because from this point on any dirt that is contacted by the hands will be carried into the splice and will make splicing more difficult.

6. The various binder groups can be separated so that the splice may be planned. Each group can be easily marked by taking its binder loose for a couple of turns and making a concentric wrap with the binders. Then the binder can be moved to the cable jacket by selecting a pair and pulling it from the group while holding the rest of the group. (See Figure I) This one pair will make the binder slide back to the cable butt. This method provides a positive unit identification. Unlike non-filled cables, the binder of the filled cable will stay in place and not ravel.

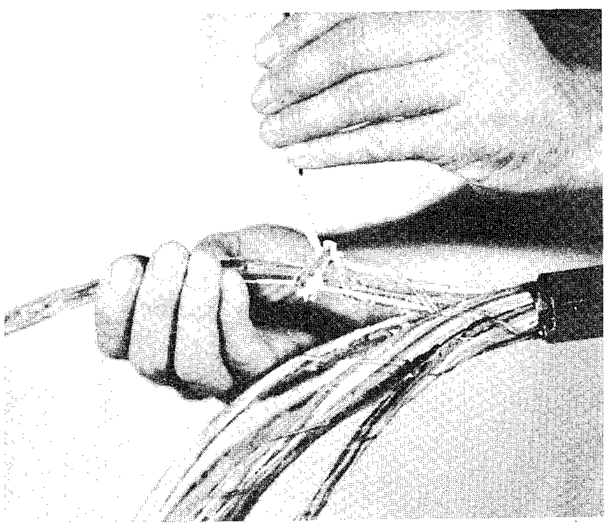

FIG. 1

7. The normal step here would be to twist together the long lay pairs so that the tip and ring do not become separated. Because of the filling compound, this step is unnecessary as it is tenacious enough to hold the conductors together during splicing so that the chances of splits are eliminated.

8. Splice conductors using the chosen method.

As would be expected, splicing time is increased due to the presence of the filling compound. The increase in time is approximately 15% for a new splicer. This time can be reduced considerably once a person becomes experienced. An experienced craftsman can splice filled cable in approximately the same time as standard cable, depending on the type of connector being used. Table IV lists splicing times of filled and non-filled cables. The connector that utilizes a machine to crimp and hold the connector significantly reduces splicing time.

TABLE IV

SPLICING TIME COMPARISON ON TF VS. STANDARD ALPETH CABLE

25 Pr. 22 Awg Cables

SPLICER NO. 1	TF Cable (UR Connectors)	17.0 Minutes
	Standard Alpeth (UR's)	14.5
	Difference	2.5
	Percent Increase	14.7
SPLICER NO. 2	TF Cable (UY Connectors)	18.0 Minutes
	Standard Alpeth (UY's)	15.0
	Difference	3.0
	Percent Increase	16.6

Average 15.6 % increase or 2.75 minutes extra for 25 pair cable.

The filled cable splicing times are times recorded for the first filled cable splices made by the splicer.

Twisted And Soldered Splices

Twisted and soldered joints on filled cable require a little special care so that a good joint results. The first consideration is stripping the insulation from the conductor. This is most easily done by using a pair of snips that have the stripping notch. The polypropylene insulation used on the conductors is quite tough and is difficult to strip by using side cutters or by using snips that do not have a stripping notch. Also, the difficulty is added to by the filling compound. Once the conductors are stripped, they can be twisted in the conventional manner. The splicer will find, however, that it is more difficult to grasp the conductors

while twisting and he will also find that continued twisting will soften his hands and he will start to lose normal twisting calluses. Once the conductors have been twisted, the soldering should be done by dipping in quite hot solder. This is necessary to float the filling compound off the conductors. To get a good bond, it is also necessary to use a non-corrosive flux which can be floated on top of the hot lead. Thus, the conductors are cleaned as they go into the lead and a good solder joint results. To protect the connections, tube type sleeves should be used rather than the butt type because the butt type sleeves will easily slide off during handling and shorts will result. Splices that have been twisted and soldered cannot be protected in the same manner as connectored splices. That is, the hand packing operation must be eliminated, as it would cause sleeves to be moved from the joints causing shorts.

Buried Splice Protection

Filled cables require some special handling for splice protection. When considering splice protection methods, we looked for ways to restore the splice to at least the integrity of the cable jacket for buried applications and ways of protecting the splices from the elements for above ground applications. All presently accepted methods and several new concepts were evaluated.

Some tips were picked up during field installations that are worthwhile mentioning. The first helpful hint is the placing of vinyl tape on the cable jacket where it is cut for the splice opening. This keeps compound from getting on the jacket and acting as a release agent. The tape should cover about six inches of the jacket. Another is the use of muslin over the splice bundle when using mechanical cases. This makes re-entry much neater, as the compound is stable enough in buried installations to be contained by the cloth.

Several methods of protecting buried splices are commercially available and most of these do a good job. The methods we have considered in most part are encapsulations, although we have looked at some of the older methods of protecting splices. Filled cables offer quite an advantage over other cables if the splice protection fails. This is because the core is protected from moisture migration. By utilizing a compound such as that used in the cable, a secondary protection can be afforded to the splice. That is, if the splice is hand packed with filling compound and an encapsulation or mechanical case is applied over it, you have double protection.

To affect this double protection for the splice, use the hand pack method and then apply over it a layer of muslin tape, over that a layer of rubber blanket to contain the compound and allow the splice to be neatly formed and then two half-lapped layers of DR tape. To make a bond between the DR tape and the jacket, the jacket should be scuffed and C-cement applied. This makes about the best bond we can get to the polyethylene jacket. The importance of this jacket bond cannot be overemphasized because this is the area where most all leaks occur and is the point of moisture entrance. Over this an encapsulation is made. Most of the encapsulations presently in use are quite good as they do not crack and are not affected by the petrolatum. They will give the physical protection needed if we provide a bond to the jacket.

Since filled cables are primarily designed for buried construction, we undertook a project to determine the best splice protection methods for direct buried splices. This study involved splice protection methods commonly in use (that is encapsulations and mechanical cases). We found that most all methods work. The primary reason for an encapsulation to fail was poor jacket bond but it was found that an excellent seal could be made with any urethane encapsulating method that was used. Compounds that were used in the test were limited to urethanes and soft materials such as petrolatums. The test was two part. The first part involved checking compatibility of the encapsulating materials with the filling compound in the cable and the second part of the test involved actually making up splices on fifty pair filled cable, and protecting them with the particular splice protection method. The completed samples were submerged in water. This water was then heated to 100 F and cooled to 0 F on a cyclic basis in an effort to simulate ground conditions through summer and winter. Although insulation resistance decreased with the length of time the materials were in the water, the compounds adequately protected the splices to a point where an operating company would not be affected. Values did not decrease below 50,000 megohm miles.

If splice re-entry is desirable, two avenues are open. The first, is the cast iron case that has been used by the industry for many years. When using this case, it is important to make some revisions in the installation procedure. First the splice should be wrapped in muslin and rubber blanket so that it can be

shaped into a uniform bundle. This bundle is then taped with DR tape, white side out, and once again white side down. The white side must extend onto the jackets of entering cables at least one inch so that all compound is contained. This is necessary because the filling compound softens the sealant used between the two halves of the splice case. Because of this taping, the length of the splice will have to be shortened by two inches, as the cable jacket normally is removed at the inside edge of the entrance port. These cases are quite time consuming to install. They can be tested with air pressure to check the seal, but this flash test does not assure that the case will maintain its seal.

A second and less time consuming method is a system using a urethane encapsulant. This product, GFC/REN HE Closure, utilizes double splice protection. The splice is hand packed with a petrolatum base compound. The splice bundle is wrapped in vinyl tape and an encapsulation is made over it in a plastic sleeve. To re-enter this unit, the plastic sleeve is removed and the urethane cut by pulling an embedded wire. To reclose the splice after re-entry, the plastic sleeve is replaced and again filled with urethane. This system is quite reliable and requires little time to prepare.

Our original thoughts on splice protection utilized a method similar to the previous one. This method consisted of packing the splice with a petrolatum base compound and installing a plastic sleeve over it for mechanical protection. This method worked well if care was taken during hand-packing, but did not work under field installation conditions. The problems arose from voids between conductors that allowed moisture to track to the connectors. Part of the problem can be attributed to the stiffness of packing compound used, but mostly to a method that is not fool-proof.

If re-entry is not desirable then several avenues are open. Listed in Appendix I are the urethane encapsulants we found suitable for use on these cables. We found that they all perform satisfactorily if the jacket is scuffed, coated with C-cement and then a build-up of DR applied, (Figure II), to compensate for the difference in expansion and contraction of the cable and encapsulating compound.

When splicing above ground in pedestals, no special procedures are necessary. Normal filled cable splicing procedures are followed. The compound should not be removed from the conductors and moisture resistant connectors must be used. When exposed to the air for a period of time the filling compound will turn an amber color and become less greasy. Thus, when pedestals are re-entered to provide service or for other work the craftsman will find the splice easier to work. The change in color of the compound does not affect the identification of pairs in the splice or affect it's protective qualities.

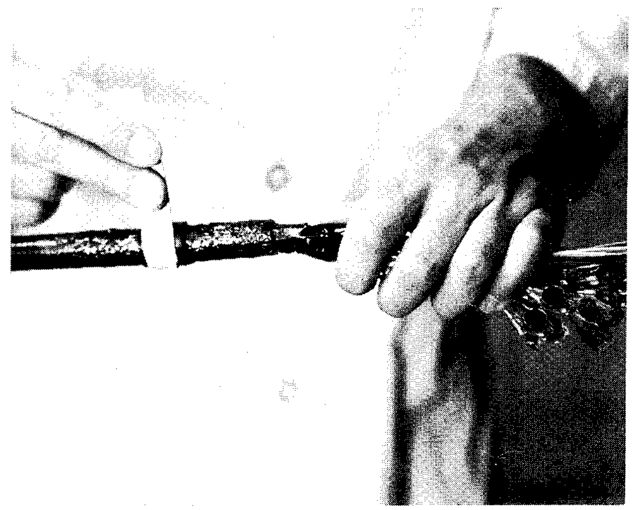

FIG. 2

Aerial Splice Protection

When aerial splicing, no special splice protection methods are necessary. A moisture resistant type connector must be used and as much of the filling compound as possible should be left on the conductors. The conductors should not be thoroughly cleaned of the filling compound as it helps to protect the splices from moisture and to protect the conductors. The use of tapes around the splice area on jackets or to hold a splice bundle should be avoided as the combination of the filling compound and the heat in the aerial cable or in the splice case may cause the adhesive on the tape to dissolve and there will be no holding power left. If ready access closures or mechanical cases are to be used, inner sheath rings that have tangs should be used to assure a good grip to the jacket and shield.

Placement of splice points is another consideration in aerial work where ready access closures are to be used because the sun's heat will raise the cable temperature to approximately 170 in certain instances. At these temperatures, the splices may drip some of the light oils. For this

reason, care should be taken so that the closures are not over places where damage to property would occur.

Installation

Installation of filled cables presents no problems, however, some factors must be considered. For example, filled cable weighs about 60% more than standard Alpeth cable. For this reason equipment chosen for transporting and installing the cable must be capable of handling this increased weight. Under most circumstances, this weight presents no problems, however, it may be a prime consideration when selecting equipment to transport the cable to the job site. Reels that would normally be transported on a pick-up truck or on a small trailer might not be transportable in as large a quantity as the operating company is accustomed to. When considering the differences in weight between filled cable and standard direct buried cable (that is double jacketed cable), the weight difference is not quite so significant. Filled cables offer some advantage during installation as they are much less compressible than the standard cables Thus when they are over-flexed while being pulled across sheaves or rollers, they are not quite so susceptible to smashing damage or shield fracture. The advantage is that the shield tends to float because it is lubricated on both sides and the corrugations do not stay in register with the corrugations that are formed in the jacket during extrusion. For this reason, the shield will not break quite as quickly as it would in a standard cable when it is subject to overflexing.

The non-compressibility of the core offers quite an advantage when the crews come in to set the pedestals because it is here that damage most often occurs. This damage is usually due to error on the part of the person installing the cable, things such as the cable being bent sharply where it leaves the plow slit and enters the trench leading to the pedestals or instances where the cable has been bent severely where it enters the pedestal because the trench is not deep enough to accommodate the depth of the pedestal. It is in these areas that the shield is broken due to bending. With the filled cable, there is less shield damage thus better continuity of shield. The rigidness of the core due to filling compound allows for bends to be made more uniformly with less care. This is due to the non-flattening characteristic of the core during bends. It can be compared to the practice of filling a pipe full of dry sand and heating it to get a uniform bend. The force required to bend filled cable is the same as that for double jacketed cable at room temperature. As the temperature decreases it becomes more difficult to bend. At -30 F, the filled cable is 30% more difficult to bend than double jacketed cable.

When back-filling trenches, the same care should be used as back-filling normal cables because we still have a problem of cut-through due to sharp objects contacting the cable jacket. Recommended practice is to back-fill with fine material, sand or loose dirt, and to make all possible efforts to keep sharp rocks away from the cable.

Although filled cables were designed primarily for buried use, they are often used in the air. The prime consideration when installing this type of cable on poles is the high weight per foot. When used on existing pole lines some consideration must be given to the sags of existing cables. For example, a typical sag and tension for 25/22 Alpeth cable is 17 inches and 1,190 pounds. Under the same conditions a 300/22 filled cable would require a sag of 63 inches and 2,580 pounds of tension. Common practice is to sag the new cable to the old. In this case severe problems would exist as it would take 30,900 pounds of tension to raise the larger cable to a 17 inch sag. Since this is an excessive tension the smaller cable and strand would have to be lengthened and resagged to the new large cable.

Cable Damage

It is inevitable during installation, that cable jackets will be damaged. With standard cables, this means that moisture or water will enter the cable either between the jackets of the double jacketed cable or directly into the core of a standard single jacketed cable. With filled cable, the damaged area is the only area of concern. That is, the water will not migrate down the cable core and ruin several hundred feet of cable. The problem is usually that the cable damage occurs and it is not known until sometime afterwards. (For instance when the cable is spliced and testing is begun.) For this reason many cable feet of standard cable are lost to moisture or water. With filled cable, the water is held out of the cable and the cable is perfectly safe until the discovery of damage is made. At this time, the cable can be opened at the damaged spot and any moisture removed and the jacket integrity restored, either through encapsulation or a case of some sort. We have found cable that was damaged and not discovered until several months later. This cable in places was under standing water, it

went through a winter freeze and moisture migration was limited to about one foot on each side of the damaged spot.

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APPENDIX I

SPLICE ENCAPSULANTS SUITABLE FOR USE ON ALP-TF TELEPHONE CABLE

Communications Technology Corporation

Q Compound

GFC Engineering and Sales Corporation

RP-6004
RP-6006

Hysol Division -The Dexter Corporation

Compound as furnished in "U" series kits

3 M Company
Scotchcast 4401

Preformed Line Products Company

3600

Rezolin, Incorporated

185 C

Western Electric

F Plug

WALT DISNEY WORLD CONTEMPORARY CABLE SYSTEM

P. J. Hartling, WED Enterprises and
W. L. Sellers, General Cable Co.

A Film and Oral Presentation

THE UNI-FIELD (BLACK MAGIC T.M.) FLAT CABLE, A NEW MULTISIGNAL TRANSMISSION LINE

Joseph B. Marshall
Ansley Electronics Corp.
Subsidiary of Thomas & Betts Corporation
Doylestown, Pennsylvania

Introduction

For applications where a multitude of signals have to be transmitted through cables in small spaces, flat cable transmission lines have been found to be the best solution. In conventional flat cables alternate ground-signal-ground conductors are positioned side by side in one plane to establish the required transmission line parameters: Characteristic impedance, velocity of propagation, attenuation and line to line interference (crosstalk). These flat cables are being used in millions of feet today transmitting signals with rise times of a few nanoseconds only, and performing quite satisfactorily. There is one aspect, however, where these types of cables are pushing the limit of their acceptability: the crosstalk from one signal line to the other. The interference between the adjacent signal lines increases as pulse rise times become faster. This crosstalk effect is mainly due to the fact that only the central part of the electromagnetic field is propagating within the cable insulation, while the outskirt of the field extends into the immediately surrounding air. At fast rise time pulses this air effect causes:

a. Excessive ringing above the "Fast crosstalk"(1) level at the Near End;

b. "Differential crosstalk"(1) at the Far End of the interconnection.

Black Magic flat cable eliminates this air effect and replaces it with a special compound plastic jacket; by that it greatly reduces crosstalk.

The Black Magic phenomenon accomplishes three important tasks:

1. Provides for a low crosstalk cable interconnection in place of high crosstalk level conventional flat cables.

2. Extends the advantages of flat cable concept into a field where miniature coaxial cables were required because conventional flat cables were too noisy.

3. Extends the field of flat cables for intercabinet wiring applications for floor use because the Black Magic jacket withstands such wear.

Physical Description

The main features of the cable are:

a. A central flat cable insulation core having low dielectric constant and low dissipation factor, embodying a multitude of conductors and

b. An all around insulator jacket distinctively different from the cable core insulation. For electrical reasons it has a high dielectric constant and high dissipation factor; for physical advantages it is self-extinguishing, has a quality for wear and abrasion resistance and seals environmentally.

The prototype cable (see Figure 1) has a polyethylene insulation for the core and a special vinyl compound for jacket. The Black Magic tradename comes from the color of the jacket and the unexpectedly good performance of this cable. (Pat. pending)

The prototype design (see Figure 2) consists of 20 signal and 21 ground conductors; the signals are round, while the grounds are rectangular. The thickness of the ground conductors is equal to the signal wire diameter.

Such conductor arrangement has many advantages:

a. The width of the rectangular conductors is chosen so that the signals may be located in alignment with given connector terminals, yet establishing the necessary spacing for the characteristic impedance between signals and grounds.

b. The insulation removal (stripping) is easier at the cable ends because both round and rectangular conductors have uniform height.

c. There is only one ground to terminate between two adjacent signals (in conventional round wire flat cables two or more grounds have to be used, partially because of crosstalk control or matching the cable signals to connector terminal locations).

d. The flat round arrangement offers an

easy identification for signals and grounds. This feature is quite helpful, particularly when signals and grounds will be terminated in two different planes (e.g. to printed circuit boards used as microstrip).

The operating temperature of the prototype cable is 80°C; however, the Black Magic[T.M.] phenomenon may be designed with high temperature insulation materials and offer the same advantages as the prototype polyethylene core cable. The prototype structure is flexible and may be bent into a radius equal to the cable thickness and straightened out without any noticeable change; it also may be folded straight back upon itself or in a 45° angle without causing any physical damage, with no ill effect on the electrical performance. The prototype cable passes the U.L. flame test for self-extinguishing properties.

Electrical Features In General

The geometry of the cable ensures a uniform polyethylene dielectric practically for the total area of the TEM field. (TEM, Transverse-electromagnetic propagation is the mode commonly excited in coaxial and open wire lines).

The main electrical parameters for multisignal transmission cables in general are:

1. characteristic impedance
2. propagation velocity
3. attenuation
4. line to line interference (crosstalk)

In the prototype Black Magic cable the first three are controlled by the polyethylene cable core, while crosstalk is limited by the special jacket.

Multisignal transmission line flat cables of conventional types have a major drawback at fast rise time pulses: to keep line to line interference at an acceptable minimum level. The surrounding air at the outer periphery of these cables raises crosstalk and in particular Far End crosstalk to such level that loads may be triggered unintentionally.

The main electrical feature of the Black Magic phenomenon is to replace this undesirable air effect with a layer of dielectric material: the jacket, which has a higher dielectric constant and higher dissipation factor than the cable core. This jacket confines the field of propagation of the individual signals to such a degree that crosstalk will improve manyfold.

It is the criteria of this design to select a geometry for the thickness of the polyethylene in coordination with the conductor arrangement, where the great majority of the electromagnetic field will propagate within the low loss dielectric and attenuation or propagation velocity will be affected very little by the surrounding jacket. In the prototype design being presented here, 98% of the field propagates in the polyethylene cable core.

However, the Black Magic cable may be designed with thinner cable cores with certain trade-offs on the propagation velocity and attenuation. In these designs the higher dielectric constant material will contribute to a composite dielectric constant by the percentage of the square root of its dielectric constant weighed by its field effect. Consequently, the propagation velocity in such cable would be somewhat slower; still, the Black Magic phenomenon will apply and crosstalk will be limited.

The present prototype cable was designed for unbalanced systems; however, the "Black Magic" phenomenon applies as well for balanced pair designs and improves crosstalk in both cases.

Characteristic Impedance

The characteristic impedance of signal transmission lines depends on the size, shape and location of the conductors and on the dielectric constant of the insulation material. In order to establish a formula with measurable properties the following basic relationship was utilized:

$$Z_o \, c \, C = 1$$

where:

Z_o = characteristic impedance, ohms, in air

c = velocity of propagation, meter per second, in air

C = capacitance, Farad per meter, in air

A simplified form of this with practical units:

$$Z_o = 1.016 \,/\, C$$

where:

C = capacitance, picofarad per foot, in air

To account for the dielectric material:

$$Z_d = Z_o / (\varepsilon)^{\frac{1}{2}}$$

where:

Z_d = characteristic impedance in cable

Z_o = characteristic impedance in air

ε = the effective dielectric constant, relative to air

To ease the prediction and calculation of the cable's characteristic impedance a formula was established based upon the dimensions of the cross-sectional geometry:

$$Z_d = \frac{1}{(\varepsilon)^{\frac{1}{2}}} 42 \cosh^{-1}(1.8x^2-(1.25x^2-1)^{\frac{1}{2}})\text{ohms}$$

where:
- $x = D/d$
- D = pitch, signal to ground
- d = diameter of conductor

The above formula was found to be in close agreement with actual measurements. It gives direct applicability for multiconductor cables where both signal and ground conductors are round wires. Therefore, further explanation is needed for the characteristic impedance of flat-round-flat conductor arrangements, the design used for the prototype Black Magic™ cable. Since the thickness of the flat conductors is equal to the signal wire diameter and the corners are radial, the following consideration was accepted:

$$D = s + d$$

where:
- s = the separation between the round and rectangular conductors

Recognizing the dimensions for the conductor arrangement in the prototype Black Magic cable:
- d = 0.0113 inch
- s = 0.00685 inch
- D = 0.01815 inch

the calculation gives Z_o = 76.2 ohm characteristic impedance in air.

Having 98 percent of the field propagating in the polyethylene and 2 percent in the jacket, results a square root of composite dielectric constant equal to 1.525; consequently, the characteristic impedance of the prototype Black Magic cable:

$$Z_d = Z_o/(\varepsilon)^{\frac{1}{2}} = 76.2/1.525 = 50 \text{ ohms}$$

Propagation Velocity

The electromagnetic energy propagates in free space with a velocity of $3\,(10)^8$ meters per second. Expressing this in more practical units on a time delay base:

TP_o=1.016 nanosecond per foot, in air and

$TP_d = TP_o(\varepsilon)^{\frac{1}{2}}$ nanosecond per foot, in cable

where:
TP_d = propagation time in cable

The signal propagation time in the prototype Black Magic cable is 1.55 nsec./foot. The polyethylene cable core without the jacket yields 1.53 nsec./foot propagation delay. These measured results are shown in Figure 3 and are comparable to calculated values based upon the assumption that 98% of the TEM field propagates within the polyethylene.These readings are taken at the 10% level of the input pulse rise time, t_r = 0.18 nanoseconds.

Observing the pictures at the 5% level (one vertical Division) 1.54 (cable with jacket) and 1.50 (cable without jacket) nanosecond per foot reveals more difference, due to the slightly larger elbow radius of the unjacketed cable. (In conventional flat cables where the cable thickness and signal-ground conductor design pitch ratio is smaller and often less than 1 (one), this elbow radius due to air effect, can develop to a serious degradation of the pulse edge.)

Attenuation

Signals transmitted through cables are attenuated along the lines. This attenuation is due to conductor losses and insulator losses; both are frequency dependent. Copper losses are affected by the square root of frequency, and insulation losses by the frequency. The measure of attenuation is expressed in decibel/foot at sine wave frequencies and by the slope change of the rise time at pulse type signals.

The shape of a selected pulse rise time (1, 5, or 10 nanoseconds, etc.) may be matched by the ascending half of an equivalent sine wave frequency through a two channel oscilloscope. Such measurements showed good agreement with the following formula:

$$t_r = 0.295/f_o$$

where: t_r = pulse rise time 10% to 90%, seconds

f_o = corresponding frequency, in Hz

Sine Wave Attenuation

Conductor losses may be expressed by the following formula:

$$A_c = 0.75\ (f_{MHz})^{\frac{1}{2}}/Z_d\ d$$

where:
A_c=attenuation of the copper conductor, dB/100 ft.
Z_d=characteristic impedance of cable, ohms
d =diameter of copper conductors, inches

The formula for insulation losses:

$$A_d = 2.78\ (\varepsilon)^{\frac{1}{2}}\ D_f\ f_{MHz}$$

where:
A_d=attenuation of the insulation, decibel/100 ft.
ε =dielectric constant, relative to air
D_f=dissipation factor

The calculated attenuation for the specimen Black Magic cable described in Figure 1 - in decibel/100 ft. units:

Frequency in MHz	10	100	1000
$A_c=(1.327)(f_{MHz})^{\frac{1}{2}}$	4.20	13.27	42.0
$A_d=(0.008)\ f_{MHz}$	0.08	0.80	8.0
$A_t=$	4.28	14.07	50.0

Figure 4 - shows the calculated and measured Sine Wave attenuation values on the prototype Black Magic™ cable.

Pulse Rise Time Attenuation

Both the edge and magnitude of pulse are attenuated through a length of signal transmission line. These losses are due to the cable conductors and insulator and will become evident by comparing the input and output shape of the pulse. In a given cable these losses are affected by the input rise time of the pulse and also by the length of cable.

To calculate the rise time attenuation a formula was developed for coaxial cables:(2)

$$T_o = 4.56(10)^{-7}(A_o^2/f_o)\ \ell^2$$

where:
T_o=time in seconds, needed for the output pulse to reach the 50% reference level of the input rise time

$A_o=A_c + A_d$ in decibel/100 ft. units

$f_o=0.295/t_r$; frequency in Hz

ℓ =length of cable in feet

t_r=input pulse rise time in seconds

This formula applies to a theoretically vertical pulse edge or at least to a very fast pulse rise time. In practice, however, we may deal with 1 or 5 nanosecond rise time pulses. When the actual input rise time is comparable or slower than this calculated rise time attenuation of the cable, both shall be considered. Taking a look at Table 3 the calculated output rise time is 2.515 nanoseconds only, with t_r = 5 nanosecond pulse input; it is obvious, however, that feeding the cable with a pulse edge of 5 nanoseconds, the output should be at least 5 nanoseconds, but cannot be less. Consequently, it seems necessary that the actual input rise time would be accounted for in the calculations. Using this method for predictions, a reasonable agreement can be found to the actual measurements. Table 1 shows the calculation of T_o. Table 2 schedules the different amplitude levels of the actual input pulse, normalizing the 10-90% rise time for one (1).

The prototype Black Magic cable was tested for rise time attenuation with three different pulse rise times:
0.18 nanoseconds
1.0 nanoseconds
5.0 nanoseconds
Results are shown in Table III in comparison with the calculated values.

Line to Line Interference (Crosstalk)

Bundled twisted pairs, triplets and conventional multisignal flat cables generally give no particular difficulties with certain transmission line parameters, such as characteristic impedance, propagation velocity or attenuation; however, line to line interference becomes a problem with fast rise time pulses or high frequency signals; for such signals coaxial cables are used at present for adequate overall performance.

Describing crosstalk between closely located signal transmission lines, the generally used terminology throughout the industry is:

1. Signal line: consists of signal and ground conductors;

2. Active line: conducting signal line;

3. Quiet line: nonconducting signal line;

4. Near End crosstalk: interference measured in Quiet line at the end where signals enter the Active line;

4a. with pulsed signals: Fast crosstalk(1) and peak crosstalk;

4b. with sinusoidal signals: the maximum level;

5. Far End crosstalk: interference measured in the Quiet line at the load end of the Active line;

5a. with pulsed signals: Differential crosstalk[1]; peak crosstalk

5b. with sinusoidal signals: the maximum level;

6. Fast crosstalk: reaches maximum magnitude when twice the propagation time of Quiet line is greater than input pulse rise time: this is a miniature replica of the input pulse; the width is equal to twice the propagation time of the Quiet line; same polarity as the input signal;

7. Peak Near End crosstalk: develops generally at the end of the Fast crosstalk; may be caused by air effect or termination mismatch;

8. Differential crosstalk: spike shaped, opposite polarity than the input pulse; Magnitude depends on air effect at the cables' outskirt and on the length of cable;

9. Peak Far End crosstalk: either polarity;

10. Matched-terminated: the input impedance of the generator (pulse or signal) is matched to the characteristic impedance of the Active line (lines);

The input impedance of the measuring instrument (oscilloscope) is matched to the characteristic impedance of the signal line being tested (Active or Quiet); all other signal lines are terminated to loads equal to their characteristic impedances.

In conventional multisignal transmission line cables the Differential Far End crosstalk causes the highest level of interference; at the same time this is the area where the Black Magic™ phenomenon is the most effective. To study the differences test results on the prototype Black Magic cable (CA-490) were compared to those measured on the basic polyethylene cable core (CA-489; the latter may be considered a good quality conventional flat cable). Figure 5 shows oscilloscope pictures of the crosstalk at the Quiet line output measured by utilizing pulse rise times: 0.18, 1, 2, 5, and 10 nanoseconds consecutively for the Active line input signal. For this test one Active line was driven adjacent to the Quiet line. This condition offers an optimum fidelity and clarity for obtaining and studying shapes of different crosstalk pictures because the characteristic impedance of the cable specimen can be matched to the impedances of the Pulse Generator and Oscilloscope (50 ohms) without special network. The improvement exhibited by the jacketed Black Magic cable may be concluded by the following tabulation:

Crosstalk in Percent

t_r nsec.	CA-489	CA-490	Improvement
10	0.3	0.05	6 times
5	0.6	0.1	6 "
2	1.5	0.3	5 "
1	3.0	0.5	6 "
0.18	8.6	1.1	7.8 "

The photographs show far end crosstalk with each of the five different pulse rise times on both pictures. On CA-489, the base lines are aligned for easier reading. The crosstalk control is clearly visible in the reduction of the spikes and the most evident at the faster rise time pulses.

The reason for this crosstalk reduction is the difference between CA-489 and CA-490: the jacket. It makes the cable thicker and it also has higher dielectric constant and higher dissipation factor than the polyethylene cable core.

A reasonable question arises: was the crosstalk reduced by the thicker cable or by the different dielectric? For an answer another cable (CA-580) was built with a polyethylene jacket around the basic polyethylene cable core with dimensions identical to CA-490. The Far End crosstalk measured on this specimen is shown on Figure 6.

Comparing these measurement to the previous two cables, the following conclusions may be taken:

1. Far End crosstalk improved with the thicker polyethylene cable compared to the thinner one. However, the Black Magic cable utilizing <u>different dielectric materials confined the crosstalk far greater.</u>

2. The differential spike (opposite polarity than the signal pulse) at fast rise time pulses still characterizes the thicker polyethylene cable, while the same is diminishing in the Black Magic cable (with t_r = 0.18 nsec. it is 2.6% in CA-580, while only 0.5% in CA-490).

For the 10 foot Black Magic prototype, the Near End crosstalk was measured with one Active line adjacent to

the Quiet line. Figure 7 shows the oscillocope picture.

The above tests were selected to give a clear evaluation on the crosstalk controlling features of the Black Magic[T.M.] type cables. However, for quantitative worst case results, tests were made driving four Active lines (two at each side of the Quiet line) on ten-foot and fifty-foot long prototype cables. The respective pictures are shown on Figure 8 and Figure 9. The highest crosstalk measured was 3.5% for Near End peak with 1 nanosecond rise time input which shows a performance much better than conventional flat cable transmission lines.

List of Figures

1. Photograph of the prototype Black Magic[T.M.] cable with insulation stripped and conductors showing at one end.

2. Cross-section of the prototype Black Magic cable.

3. Oscilloscope pictures of the propagation delay measurements on 10 foot cable.

   a. Black Magic cable (polyethylene cable core with higher dielectric constant jacket CA-490).

   b. Polyethylene cable core only (CA-489).

4. Sine wave attenuation on the prototype Black Magic cable, calculated and measured values.

5. Oscilloscope pictures of Far End crosstalk measurements on 10 foot cables, with one (1) Active line.

   a. Black Magic cable (polyethylene cable core with higher dielectric constant jacket CA-490).

   b. Polyethylene cable core only (CA-489).

6. Oscilloscope picture of Far End crosstalk measurement on thick polyethylene cable (polyethylene cable core with polyethylene jacket: CA-580), 10 foot long, one (1) Active line.

7. Oscilloscope picture of Near End crosstalk measurement on prototype Black Magic cable CA-490, 10 foot long, one (1) Active line.

8. Oscilloscope pictures of crosstalk measurements (Near End and Far End) on prototype Black Magic cable, CA-490, 10 foot long, four (4) Active lines, $t_r = 1$ and 5 nsec.

9. Oscilloscope pictures of crosstalk measurements (Near End and Far End) on prototype Black Magic cable, CA-490, 50 foot long, four (4) Active lines, $t_r = 1$ nanosecond.

List of Tables

1. Calculation of T_o for the prototype Black Magic cable CA-490, 10 foot long.

2. Amplitude levels of a pulse edge with 10-90% referenced to one (1).

3. Pulse edge attenuation of prototype Black Magic cable CA-490, 10 foot long, calculated and measured values.

Acknowledgement

Thanks and appreciation are due to Leon Arrimour (Thomas & Betts Plastics Division) for the successful jacket applying process with different materials and to Robert B. Linville (Ansley Electronics Corp.) for his tireless effort in the preparation, termination and testing of specimens and for the spirited discussions throughout the program.

References

1. Catt, Ivor, Crosstalk (Noise) in Digital Systems, "IEEE Transactions on Electronic Computers", Vol. EC-16, No. 6, December 1967.

2. Kerns, Q.; Kirsten, F.; Winningstad, C.; Counting Note, Pulse Response of Coaxial Cables, (University of California, Lawrence Radiation Laboratory, Berkley) File No. CC-2-1B (1) Rev., July 29, 1966.

Table I - Calculation of T_o for the prototype

Black Magic[T.M.] cable CA-490 10 foot long

input t_r amplitude percent level	output t_r normalized for T_o when input pulse is 90° vertical
10	.17
20	.28
50	1.0 (T_o)
60	1.65
70	3.06
80	7.09
90	28.8
The 10% to 60% t_r is thus $(1.65-0.17)T_o = 1.48\ T_o$	

For rise time degradation measurements, the following pulses were used:

input t_r, nanosecond	.18	1.0	5.0
corresponding f_o, MHz	1639	295	59
$f_{MHz}^{\frac{1}{2}}$	40.48	17.18	7.68
A_{cu} dB/100 ft. $(=1.37\ f_{MHz}^{\frac{1}{2}})$	53.72	22.79	10.19
A_d dB/100 ft. $(=.008\ f_{MHz})$	13.11	2.36	.47
A_o, Attenuation dB/100 ft.	66.83	25.15	10.66
A_o^2	4466.25	632.52	113.6
A_o^2/f_o	2.725	2.144	1.926
$4.56\ (A_o^2/f_o)$	12.4259	9.777	8.7827
T_o nanosecond for 10 ft.	.1242	.09777	.0878

TABLE II Amplitude levels of a pulse edge with 10-90% referenced to (1).

Amplitude of input pulse rise time	Factor when rise time normalized for (1)
10% - 50%	.46
10% - 60%	.56
10% - 70%	.68
10% - 80%	.82
10% - 90%	1.0

TABLE III Pulse edge attenuation of prototype Black Magic™ cable CA-490, 10 foot long, calculated and measured values

Rise time Amplitude	Factor per Table I	Time Part of T_o per Table I	Time Part of Actual Pulse rise time per Table II	Output Pulse Rise Time Calculated	Output Pulse Rise Time Measured
		n a n o s	e c o n d		
Pulse rise time = .18 Nsec. T_o = .12426 Nsec.					
10-50%	.83 T_o	.103	.083	1.86	.20
10-60%	1.48 T_o	.184	.101	.285	.25
10-70%	2.89 T_o	.359	.123	.482	.40
10-80%	6.92 T_o	.860	.148	1.008	.80
10-90%	28.63 T	3.56	.18	3.74	2.95
Pulse rise time = 1 Nsec. T_o = .09777 Nsec.					
10-50%	.83 T_o	.081	.46	.541	.60
10-60%	1.48 T_o	.145	.56	.705	.72
10-70%	2.89 T_o	.283	.68	.963	.88
10-80%	6.92 T_o	.677	.82	1.497	1.24
10-90%	28.63 T	2.799	1.0	3.799	3.12
Pulse rise time = 5 Nsec. T_o = .08783 Nsec.					
10-50%	.83 T_o	.073	2.3	2.373	2.50
10-60%	1.48 T_o	.130	2.8	2.93	2.95
10-70%	2.89 T_o	.254	3.4	3.654	3.60
10-80%	6.92 T_o	.608	4.1	4.708	4.60
10-90%	28.63 T_o	2.515	5.0	7.515	6.50

Mr. Marshall is engineering manager, and has been associated with Ansley Electronics Corporation, for the past eleven years.

He is an electrical engineer by profession, was born and educated in Hungary, came to the United States in 1957. Since then he has been working in the field of electrical interconnections, cables, connectors, coaxial devices.

Mr. Marshall holds several patents, has presented many papers. His latest contribution is a chapter on "Formed High Frequency Circuits" to be included in "Handbook of Wiring, Cabling and Interconnecting for Electronics"; the book will be published by McGraw-Hill next year.

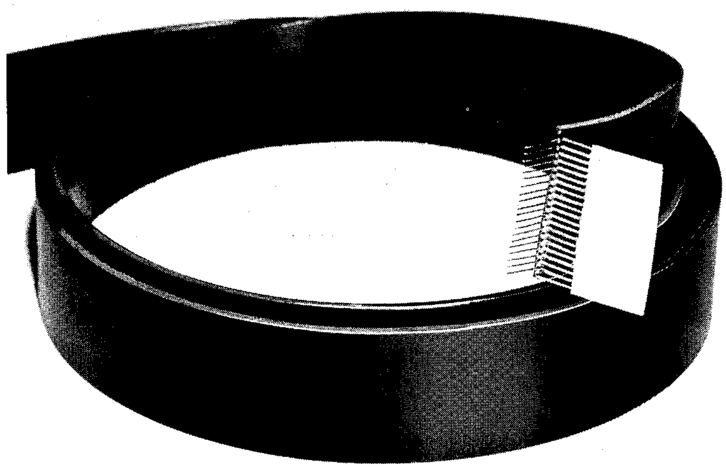


Figure 1 - Photograph of the prototype Black Magic™ cable with insulation stripped and conductors showing at one end.

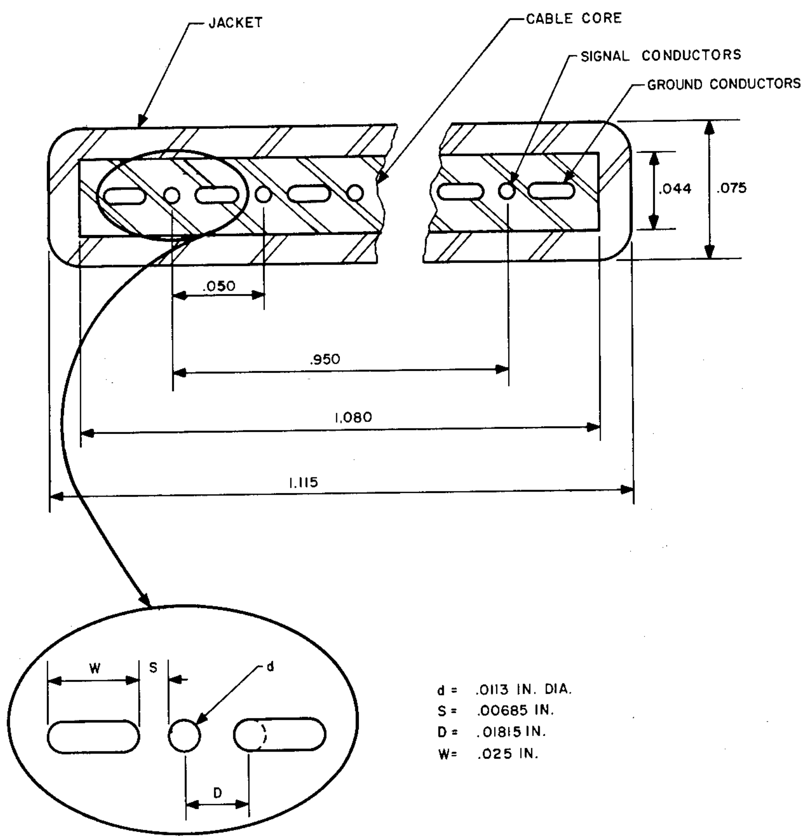
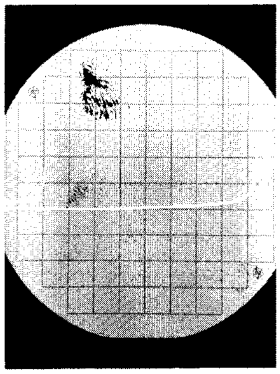


Figure 2 - Cross-section of prototype Black Magic cable (CA-490)



CA-490:

Total delay at 10% level	16.5 nsec.
Delay in test adapter	1.0 "
Total delay for cable	15.5 nsec.

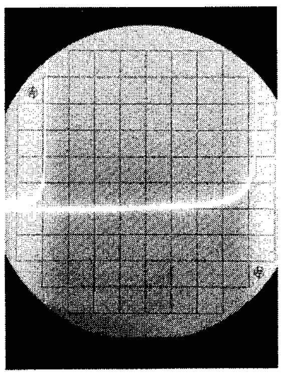
Prop. time = 1.55 nsec/foot

$(\varepsilon)^{\frac{1}{2}} = 1.525$
$\varepsilon = 2.327$

Total delay at 5% level	16.4 nsec.
Delay in test adapter	1.0
Total delay for cable	15.4

Prop. time = 1.54 nsec/foot

$(\varepsilon)^{\frac{1}{2}} = 1.516$
$\varepsilon = 2.30$



CA-489:

Total delay at 10% level	16.3 nsec.
Delay in test adapter	1.0
Total delay for cable	15.3

Prop. time = 1.53 nsec/foot

$(\varepsilon)^{\frac{1}{2}} = 1.506$
$\varepsilon = 2.27$

Total delay at 5% level	16.0 nsec.
Delay in test adapter	1.0
Total delay for cable	15.0

Prop. time = 1.5 nsec/foot

$(\varepsilon)^{\frac{1}{2}} = 1.476$
$\varepsilon = 2.18$

Figure 3 - Propagation delay measurements on the prototype Black Magic™ cable (CA-490) and on the polyethylene cable core (CA-489)
Length of test specimens: 10 foot
Test Equipment: H.P. #1415A TDR
Test Adapter: Ansley's #604-198
Horizontal scale: 2 nsec/Div.
Vertical scale: 5% of pulse amplitude/Div.

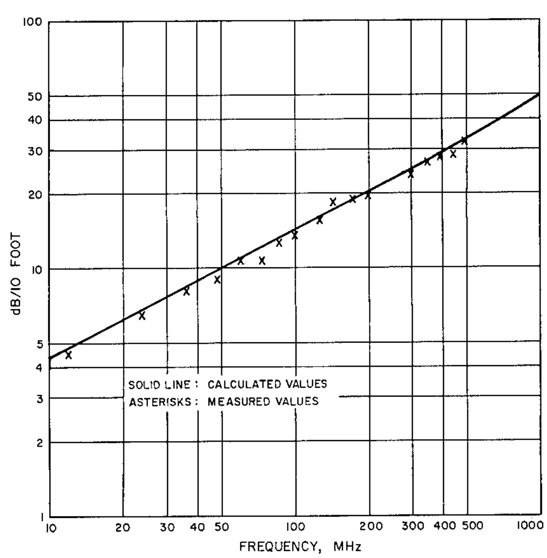
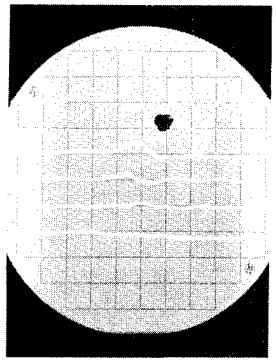
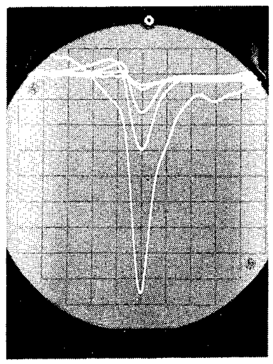


Figure 4 - Sine wave attenuation of prototype Black Magic cable (CA-490)



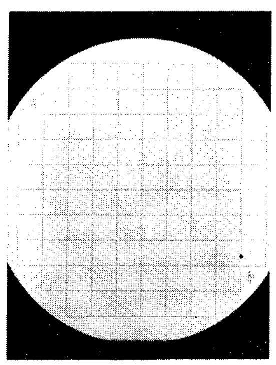
t_r nsec.	horiz. scale nsec./Div.	crosstalk %
	CA-490	
0.18	1	+ 1.1
1.0	1	+ 0.5
2.0	4	+ 0.3
5.0	4	+ 0.1
10.0	20	0.05

(t_r = pulse rise time at Active line input)



	CA-489	
10.0	10.0	-0.3
5.0	5.0	-0.6
2.0	2.0	-1.5
1.0	1.0	-3.0
0.18	0.25	-8.6

Figure 5 - Far End crosstalk measurements on the prototype Black Magic™ cable (CA-490) and on the polyethylene cable core (CA-489); one (1) Active line
Length of test specimens: 10 foot
Test Equipment: H.P. 1415A TDR and rise time converters
Test Adapter: Ansley's #604-198
Vertical scale: 1% crosstalk per Division compared to the input pulse amplitude.

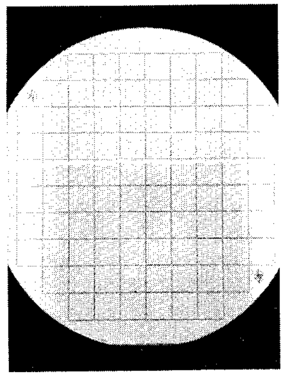


t_r = 0.18 nsec.

crosstalk = -2.6%

(t_r = pulse rise time at Active line input)

Figure 6 - Far End crosstalk on polyethylene jacketed cable CA-580, encapsulating the basic polyethylene cable core: CA-489 one (1) Active line
Length of test specimen: 10 foot
Test equipment: H.P. #1415A TDR
Test Adapter: Ansley's #604-198
Horizontal scale: 0.4 nsec/Div.
Vertical scale: 1% crosstalk per Division compared to the input pulse amplitude

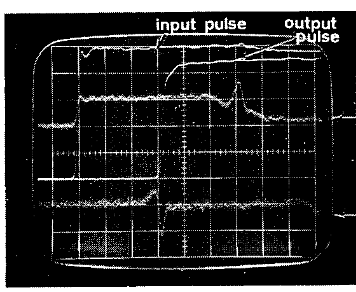


t_r = 1 nsec.

Fast crosstalk: 0.9%

Peak crosstalk: 1.5%

Figure 7 - Near End crosstalk measurement on prototype Black Magic™ cable (CA-490); one (1) Active line;
Length of specimen: 10 foot
Test Equipment: H.P. #1415A TDR + 1 nsec. rise time converter
Test adapter: Ansley's #604-198
Horizontal scale: 4 nsec./Div.
Vertical scale: 1% crosstalk per Division compared to the input pulse amplitude.



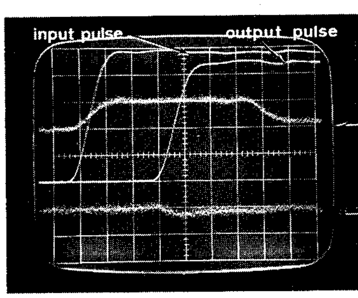
t_r = 1 nsec.

Near End crosstalk %

D.C. level	2.3
Peak	3.5

Far End crosstalk %

+	0.93
-	2.5



t_r = 5.1

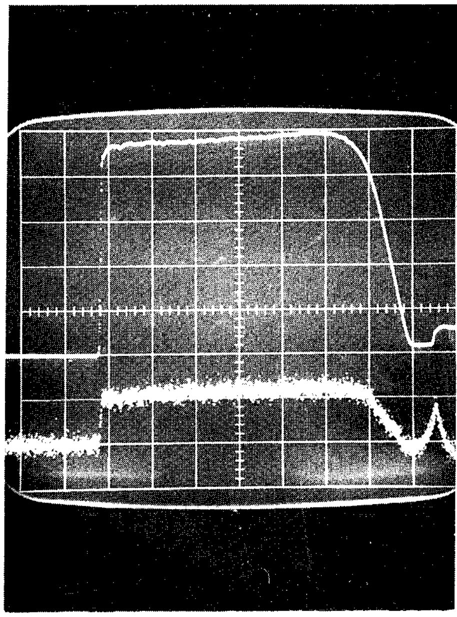
Near End crosstalk %

D.C. level	2.04
Peak	2.04

Far End crosstalk %

+	0.0
-	0.41

Figure 8 - Crosstalk measurements (Near End, Far End) on prototype Black Magic™ cable (CA 490); four (4) Active lines
Length of specimen: 10 foot
Test equipment: H.P.#8000A pulser and 5 nsec. rise time converter; Tektronix #561A scope with 3T77A and 3S1 plug in units
Test adapter: Ansley's #604-200
Horizontal scale: 5 nsec./Div.
Vertical scale:
Active line: 0.5 V/Div.
Quiet line : 0.05 V/Div.

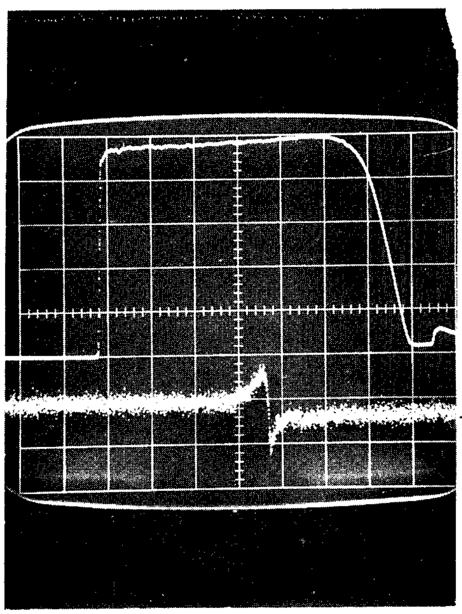


Near End crosstalk

Input pulse

Crosstalk

Crosstalk % = 2.13



Far End crosstalk

Input pulse

Crosstalk

Crosstalk % = +1.7 / -2.13

Figure 9 - Crosstalk measurements (Near End, Far End) on prototype Black Magic T.M. cable: CA-490; four (4) Active lines
Length of specimen: 50 foot
Test Equipment: H.P. #8000A pulser, Tektronix #561A scope with 3T77A and 3S1 plug-in units
Test adapter: Ansley's #604-200
Horizontal scale: 20 nsec./Div.
Vertical scale:
Active line: 0.5 V/Div.
Quiet line : 0.05 V/Div.

ADVANCES IN COMPUTER CONTROLLED MEASUREMENTS OF CABLE PARAMETERS

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ABSTRACT

Since 1967 computer-controlled test systems of the type described in this paper have been used for the rapid automatic test and evaluation of parameters of multiconductor telephone cables ranging in lengths from 200 to 20,000 feet. These parameters are important in the design and manufacture of cables by determining transmission efficiency, crosstalk and noise. These systems have evolved into second and third generation versions, with improvements in measurement techniques and operational utility. In addition to measurements of Mutual Capacitance, Capacitance Unbalance to Ground and Pair-to-Pair Capacitance Unbalance measurements of Capacitance Unbalance to Shield, Mutual Conductance, Conductor Resistance and Conductor Resistance Unbalance can now be made with the same system. This paper describes the structure of these automatic systems and some of the current and future capabilities.

INTRODUCTION

In the design and manufacture of paired telephone cable, capacitive and resistive relationships of conductors are used to determine transmission characteristics. Large cables are made up of units containing up to 100 twisted pairs each. Since there are 4950 two-pair combinations in a 100-pair unit, measurements of all pairs and two-pair combinations and the computations necessary for a statistical report makes an automatic computer controlled system highly desirable.

Since the first Automatic Cable Capacitance Test System was installed in 1967[1], many improvements and expanded capabilities have led to the introduction of second generation systems (Figure 1). In addition to measurements of Mutual Capacitance, Capacitance Unbalance to Ground and Pair-to-Pair Capacitance Unbalance, new measurements can now be performed such as Capacitance Unbalance to Shield, Mutual Conductance, Conductor Resistance and Conductor Resistance Unbalance. Emphasis was put on decreasing test time, improving operator convenience and simplifying maintenance. From one to three 100 cable-pair fanning fixtures can be connected to a system. The operator console includes a teletypewriter, a control panel, a high speed paper tape reader and a memory cathode ray tube. The keyboard of the teletypewriter and the control panel enable the operator to enter cable parameters and test modes into the systems computer. The CRT display is used to provide rapid operator displays of error messages, summaries and statistics, and a magnetic tape recorder serves to store test results for further off-line statistical analysis. The teletypewriter output is used if a record of all measured or calculated parameters is desired.

DEFINITIONS OF CABLE PARAMETERS

The cable parameters measured by the system: Mutual Capacitance, Capacitance Unbalance to Ground, Capacitance Unbalance to Shield, Mutual Conductance, Pair-to-Pair Capacitance Unbalance, Conductor Resistance and Conductor Resistance Unbalance are defined in Figure 2. All capacitance and conductance tests are made at 1 kHz.

Mutual Capacitance - Mutual capacitance is defined as the capacitance between the two conductors of a cable pair.

Mutual Conductance - Mutual conductance is defined as the conductance between the two conductors of a cable pair.

Mutual capacitance and conductance are closely related to the insertion loss of a cable pair.

Capacitance Unbalance to Ground - Capacitance unbalance to ground is the difference in the direct capacitances of the wires of a cable pair to all other cable conductors and shield. The unbalance in the capacitance to ground of the two wires of a pair determines its susceptibility to noise pickup and is sometimes referred to as the "noise capacitance unbalance".

Capacitance Unbalance to Shield - Capacitance unbalance to shield is similar to the capacitance unbalance to ground except that all other cable pairs not being tested are grounded.

Pair-to-Pair Capacitance Unbalance - Pair-to-pair capacitance unbalance is the capacitance that must be added to or subtracted from the capacitance between one wire of one pair and one wire of another pair to balance the two-pair network.

The unbalance in the capacitance between the conductors of any two pairs provides an indication of the amount of voiceband crosstalk to be expected in service.

Conductor Resistance and Conductor Resistance Unbalance - The conductor resistance is the series resistance of each wire and the conductor resistance unbalance of a cable pair is the unbalance

of the series resistances of the two wires of a cable pair.

These parameters provide an indication of attenuation and crosstalk.

MEASUREMENT TECHNIQUES

Capacitance-Conductance Bridge - The usual way to measure cable capacitances and conductances requires a bridge that is balanced to ground. It is extremely difficult, however, to maintain a balanced-to-ground condition in an automatic system. Therefore, the system described uses a three-terminal, transformer-ratio-arm bridge shown in Figure 3.

Two wires are connected to the unknown and detector terminals of the bridge. Any capacitance up to 1 μF between either of these terminals and ground is connected across the oscillator or detector and does not affect the accuracy of the measurement. In the example shown C_1 is being measured.

If the two wires are connected to the unknown and standard terminals and the core of the cable under test to the detector terminal of the bridge as shown in Figure 4, the capacitance unbalance to ground (C_2-C_3) is measured directly.

Capacitance Unbalance to Shield - The capacitance C_x between the cable shield and all other conductors can be as high as 3.5 μF for a 20,000 foot cable. The direct differential measurement of the capacitance unbalance to shield is therefore not practical due to low detector sensitivity. A special measurement technique, shown in Figure 5, overcomes this problem. Two measurements are required to determine the capacitance unbalance to shield:

1) Part (a.) of Figure 5. The cable pair under test is connected to the unknown and standard arm of the bridge. All other cable pairs are connected together and to ground. The shield is connected to the input of a non-inverting amplifier shunted to ground by a reference capacitor C_{Ref}. The amplifier, with gain k, is connected to the detector terminal of the bridge through a coupling capacitor C_c. At balance, the bridge reading C_A is proportional to the capacitance unbalance to shield:

$$C_A = (C_2 - C_3) \frac{kC_c}{C_2 + C_3 + C_x + C_{Ref}}$$

2) Part (b.) of Figure 5. The reference capacitor C_{Ref} is connected between the unknown terminal of the bridge and the input of the amplifier. The shield is connected between the amplifier input and ground. All cable pairs are connected together and to ground. At balance, the bridge reading C_B is proportional to C_{Ref}:

$$C_B = C_{Ref} \frac{kC_c}{C_2 + C_3 + C_x + C_{Ref}}$$

These two bridge readings yield the capacitance unbalance to shield:

$$(C_2 - C_3) = C_{Ref} \frac{C_A}{C_B}$$

This equation shows that only the absolute value of the reference capacitor C_{Ref} has to be known accurately. The long term gain stability of the amplifier and the stability of the coupling capacitor is of secondary importance.

The range of capacitance unbalance to shield that can be measured by the system for a given shield-to-ground capacitance C_x is limited by the maximum voltage input the capacitance bridge can withstand and the equivalent noise input of the amplifier:

$$10^{-4} \leq \frac{C_2 - C_3}{C_x} \leq 1.5 \times 10^{-2}$$

Mutual Conductance - The true mutual conductance G of a cable measured on the capacitance-conductance bridge is equal to the difference of the measured apparent mutual conductance G_m and an error term G_e:

$$G = G_m - G_e$$

G_e is the error introduced by the d.c. lead resistance connecting the fanning fixture to the test system and the d.c. loop resistance of the cable pair under test:

$$G_e = \frac{1}{3} (R_a + R_x) C_{mut}^2 w^2$$

where R_a = d.c. loop resistance of the test leads

R_x = d.c. loop resistance of the cable pair

C_{mut} = mutual capacitance of the measured cable pair

$w = 2 \pi f$; $f = 1$ kHz

Two methods can be used to determine the loop resistance of the cable pairs:

R_x can be a predetermined constant for each wire gauge or it can be measured first on each cable pair in a separate test sequence and stored in the computer memory.

Even if G_e can be determined to a good accuracy, the true mutual conductance can be in error by a large percentage, because G_m and G_e are of the same magnitude for long cables.

Conductor Resistance and Conductor Resistance Unbalance - Two methods are used at the present time to measure these parameters:

1) The conductor resistance of each wire is measured at 1 kHz with the three-terminal capacitance-conductance bridge. The errors introduced by switch-contact and internal system resistance can be minimized by separate reference measurements. This method has the advantage of simplicity and yields good accuracy for conductor resistance, but it requires four measurements per wire. The conductor resistance unbalance accuracy for short cables (conductor resistance of less than 10 Ω) is poor due to resistance variation between leads from the fanning fixture to the scanner, which are in the order of ± 10 mΩ. The error introduced by measuring the conductor resistance at 1 kHz rather than at d.c. due to skin and proximity effects are negligible.[2]

2) The conductor resistance of each wire is measured at d.c. with a four-terminal digital ohmmeter. Internal system resistance does not introduce errors with a four wire measurement. This second method is more precise than the first one but requires additional instrumentation and a four-wire scanner and fanning fixture.

THE SYSTEM

The basic system accommodates up to 100 cable pairs connected to a single fanning fixture in one or two groups. To take full advantage of the high measurement speed of the test system, an additional two fanning fixtures can be connected to the system to allow the operator to connect a cable to one fixture while a test is in progress on another cable.

A simplified block diagram of a 300 cable pair test system is shown in Figure 6. It includes a reed-relay scanner for the automatic connection of 600 cable wires, an automatic capacitance-conductance bridge for parameter measurements, a minicomputer for control and data processing, a teletypewriter, a control console and CRT for operator control, a magnetic tape recorder for data storage for off-line analysis, and a computer/system interface unit.

The computer used in this system is a Digital Equipment Corporation PDP-8/e. The computer memory can be expanded from the basic 4k, 12-bit words to 32k, 12-bit words in 4k increments, depending on how many tests have to be performed and how detailed the test reports have to be.

Before a set of test sequences is started, the operator has to enter pertinent cable data into the computer via the teletypewriter keyboard (number of pairs, cable length, conductor gauge, cable temperature, etc.). The system then checks automatically for connection errors (open connections, near end or far end shorts, crossed pairs) and waits for an operator decision is one is found. During each test sequence, measurement results which are out of tolerance produce error messages which normally do not require operator intervention.

At the end of a test sequence, a system self-check is performed using a calibrated network which simulates two 10,000 foot cable pairs. If a system malfunction is detected, an error message is displayed on the system operator console.

Following the successful completion of each test sequence, a summary of the final computed results and test limits is displayed on the operator console. A typical CRT display is shown in Figure 7. Display (a) shows some error messages which require operator intervention such as cable shorts, crossed pairs and open connections. Display (b) shows a statistical summary for a Mutual Capacitance test sequence. Figure 8 shows a typical teletypewriter output.

The basic accuracy of the capacitance-conductance bridge is 0.1%. Variation in system and fanning fixture stray capacitance and series resistance between measurement paths set the accuracy for the complete system (including fanning fixtures) to the following values for cable lengths from 200 ft. to 20,000 ft.:

Mutual capacitance: ± 0.25%
Mutual conductance: ± 0.05 Micromhos
(for cable lengths below 1000 ft.)
± 0.5 Micromhos
(for cable lengths above 1000 ft.)
Capacitance unbalance to ground (or shield):
± (4 pF + 4 pF/1500 ft.)
Pair-to-pair capacitance unbalance:
$\pm\ (4 + 0.15\ \sqrt{\text{length}})$ pF
Conductor resistance (1 kHz):
± (0.5% + 20 Milliohm)
Conductor resistance (d.c.):
± (0.1% + 1 Milliohm)

CONCLUSION

The present second-generation test systems are fast, highly reliable, accurate, self-checking and fully automatic. They can be used profitably as a quality control tool or in the design of new types of communication cables. The time saving over comparable manual systems is on the order of 10:1 or greater, depending on the data analysis performed.

Telephone cables will have to be manufactured to increasingly tighter specifications in order to be used in modern communication systems. Cable manufacturers will have to test more transmission line parameters of larger cable-pair samples to assure compliance with user specifications.

To fulfill present and future needs of the

cable industry, a third generation of Automatic Cable Test Systems, now under development, will include measurement capabilities for inductance and near-end or far-end crosstalk for 25, 50 or 100 cable-pair samples at frequencies of 150 kHz, 772 kHz and 3.16 MHz. These systems will be able to measure far end crosstalk of at least -110 dB at 150 kHz.

Peter P. Jorrens (M'60) received a technical degree in France in 1957 and the M.S.E.E. degree from Northeastern University, Boston, Mass., in 1963.

He was active in geophysical field service in France and after coming to this country in 1959, worked for LFE on rf circuit designs, for the Mitre Corporation on digital-display systems, and for Acton Laboratories on microwave and rf systems. He joined the General Radio Custom Products Operation in 1969. Currently, he is with the General Radio Company, Concord, Mass.

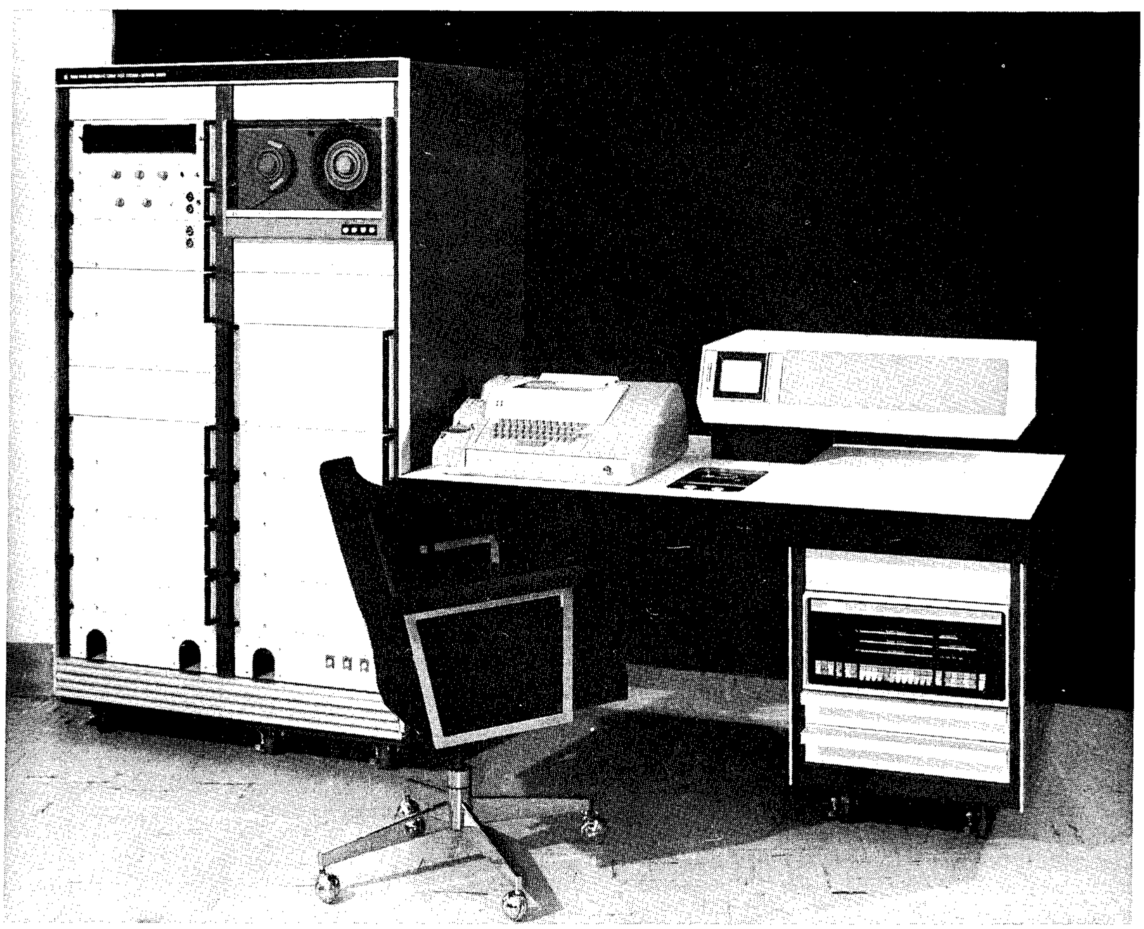

Figure 1

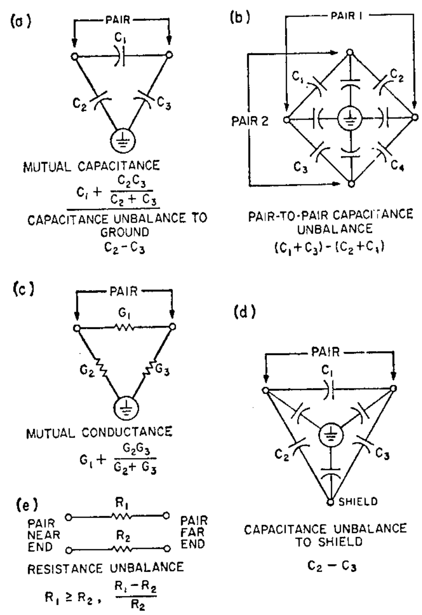

Figure 2

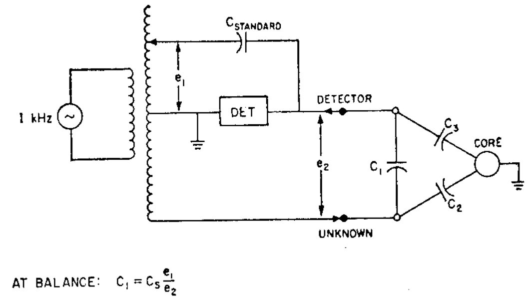

Figure 3 - Transformer-ratio-arm bridge, direct measurement of C_1.

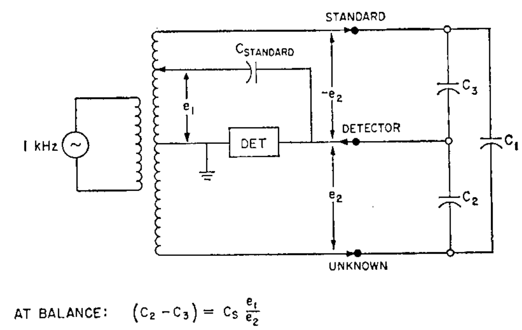

Figure 4 - Transformer-ratio-arm bridge, differential measurement of (C_2-C_3).

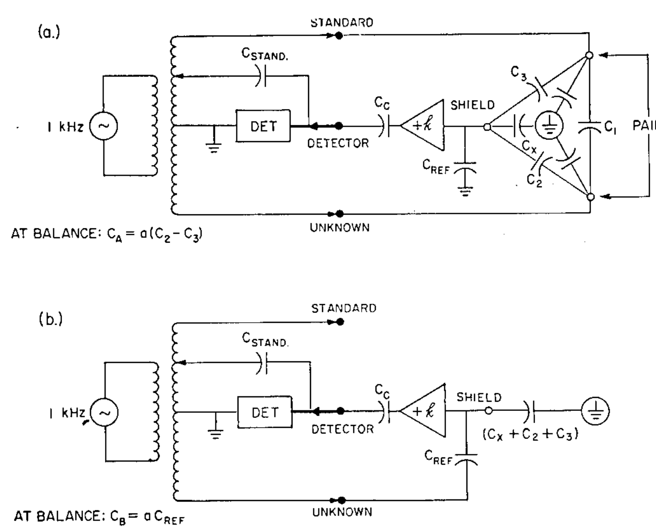

Figure 5 - Transformer-ratio-arm bridge, modified to eliminate effect of large stray capacitance.

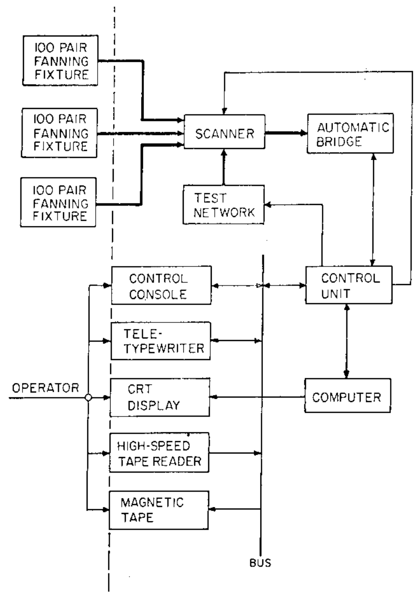

Figure 6 - Simplified block diagram of a 300-pair system with options.

```
IDENTIFICATION DATA (MUT):
ANY 42 CHARACTERS
PAIRS:  10H
LENGTH (FEET):  10030
TEST FIXTURE NO:  2

SHORT: PAIR XX R
SHORT: PAIR YY C
SHORT: PAIR ZZ S

MUTUAL ERROR THRESHOLD:    XXX.XXX PF
C1 LOW: PAIR XX   XXX.XXX PF R
C1 LOW: PAIR XX   XXX.XXX PF S
MUTUAL ERROR: PAIR XX   XXX.XXX PF/MILE
C1 LOW: PAIR YY   YYY.YYY PF R


MUTUAL CAPACITANCE AVERAGE:    XXX.XXX NF/MILE
                       LIMIT:    XXX.XXX NF/MILE
STANDARD DEVIATION:    XXX.XXX PF/MILE
        LIMITS PULP:    XXX.XXX PF/MILE
                PIC:    XXX.XXX PF/MILE
COEFFICIENT OF DEVIATION:    XX.XX %

END OF TEST
```

Figure 7 - Typical CRT displays.

```
IDENTIFICATION DATA
SAMPLE MEASUREMENT FOR C MUT, UNB GND AND P-P UNB IN ALL MEAS AND AUTO
PAIRS:   2
LENGTH (FEET):   506


MUTUAL
ERROR THRESHOLD      2.02 NF

 PAIR       MUTUAL          C1          C2          C3
    1    83.73 NF/MI     3.58 NF     8.90 NF     8.85 NF
    2    84.63 NF/MI     3.02 NF    10.16 NF    10.19 NF

MUTUAL DISTRIBUTION: CELL NUMBERS ARE CELL CENTER VALUE NF/MI

     L  70.9   72.9   74.9   76.9   78.9   80.9   82.9   84.9   86.9   88.9
     0     0      0      0      0      0      0      1      1      0      0

  90.9   92.9   94.9   96.9   98.9  100.9  102.9  104.9  106.9  108.9      H
     0      0      0      0      0      0      0      0      0      0      0

AVERAGE   0.0841 UF/MI      COEFF OF DEVIATION    0.53 %
STD DEVIATION  450.13 PF/MI  LIMITS: PULP   90.00  PIC   87.00 NF/MI
NUMBER OF TESTS    2

UNBALANCE TO GROUND
PAIR LIMIT  449.99 PF/1500 FT    AVG LIMIT  114.99 PF/1500 FT


 PAIR    UNBAL        C2          C3
    1    51.49 PF    8.90 NF     8.85 NF
    2 -  24.49 PF   10.16 NF    10.19 NF

UNBALANCE TO GROUND DISTRIBUTION: CELL NUMBERS ARE CELL MAX PF/1500 FT

   100    200    300    400    500    600    700    800    900   1000
     1      1      0      0      0      0      0      0      0      0

  1100   1200   1300   1400   1500   1600   1700   1800   1900   2000      H
     0      0      0      0      0      0      0      0      0      0      0

AVERAGE  112.64 PF/1500 FT
STD DEVIATION FROM BALANCE  119.54 PF/1500 FT
NUMBER OF TESTS    2

PAIR-TO-PAIR UNBALANCE
C.U. LIMIT  101.67 PF      SKIP LIMIT  12.45 % OF C.U. LIMIT

C.U.  DISTRIBUTION: CELL NUMBERS ARE CELL MAX  % OF C.U. LIMIT

   2.5    5.0    7.5   10.0   12.5   15.0   17.5   20.0   22.5   25.0
     1      0      0      0      0      0      0      0      0      0

  27.5   30.0   32.5   35.0   37.5   40.0   42.5   45.0   47.5   50.0      H
     0      0      0      0      0      0      0      0      0      0      0

STD DEVIATION FROM BALANCE     1.24 % OF C.U. LIMIT
NUMBER OF TESTS    1     COMBINATIONS SKIPPED    1

END OF TEST-TYPE CR TO RESTART
```

Figure 8 - Typical printout

HIGH FREQUENCY POWER BREAKDOWN OF COAXIAL CABLES

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ABSTRACT

An investigation of RG-58/U, RG-214/U, RG-218/U, cables, their equivalents utilizing polytetrafluoroethylene and silicone, and other commonly used types of RF cables was conducted to determine their high frequency power performance and breakdown. Power versus frequency curves revealed that regardless of cable size or dielectric the power handling capability decreases as frequency increases. At high frequency continuous wave (CW) power cables using polytetrafluoroethylene exhibited the best power handling capability. However cables with polyethylene surpassed those with polytetrafluoroethylene in handling pulse power.

INTRODUCTION

The information available to a designer of high frequency power systems concerning the ability of radio frequency (RF) cables to carry high power at high frequency has been limited to assumptions based on historical cases of similar systems. Accurate selection of the most suitable type of RF cable for high power systems requires information on the factors that affect performance in the transmission of continuous wave (CW) and pulse power. In an attempt to alleviate this situation an experiment was designed to determine the high frequency power performance and breakdown of RF cables. The experiment was done by the Boeing Company, Wichita, Kansas, under Navy Contract N00 140-71-C-0003 and this paper is based on the final report of this contract.[1]

The performance of RF cables under high frequency power generally depends on the fabrication and the material used in the basic design, which consists of an inner conductor, a dielectric and an outer conductor. The power handling capabilities of the cable depend mainly on the type and quality of the dielectric. Polytetrafluoroethylene, polyethylene and silicone are the only dielectrics considered in this paper. The cable breakdown at high frequency is a function of the thermal and ionic resistance of the dielectric. Several investigators[2,3,4] have made studies of these two properties of dielectrics.

BACKGROUND

The quality of uniformity of the cables insulated with the dielectrics considered in this paper may be degraded during the cable fabrication process whereby an amount of air may be trapped between the conductors and the dielectric of the cable. Furthermore, very few extruded dielectrics are completely free of air voids. The size and shape of an air void in a dielectric will affect the continuous power handling capabilities of the cable. Spherical voids will withstand higher voltages than voids with any other geometry.[5] The geometry of the voids controls the configuration of the electric field across the void. The thermal breakdown of the cable is also influenced by the size and configuration of the air voids. The air trapped within the cable will ionize causing corona discharges which will deteriorate the dielectric and eventually result in a cable failure. The failure mechanism can be of two types: treeing or puncture. Treeing is caused by ionization of the gas trapped in the small voids of the extruded dielectric. As the field intensity in the cable dielectric is increased the voltage gradient across the gas in the dielectric voids is increased and finally the gas is ionized. After ionization of the gas, a portion of dielectric breaks down and creates a conductive path between the void and the conductor. This may not cause a complete failure of the cable but will degrade the dielectric, shorten the life of the cable and reduce its power handling capacity considerably. If the treeing is severe complete failure will occur. Although the electric field is strongest at the surface of the inner conductor of a coaxial cable, severe

ionization has been reported in the outer surface of its dielectric.[6] Treeing may be responsible for such a partial failure. This type of ionization is shown in Figures 1, 2 & 3. The second failure mechanism is the puncture mode where the dielectric is completely punctured by the bombardment of ions from the ionized gases trapped between the conductors and the dielectric. Complete puncture of the cable dielectric can also be caused by the combination of the treeing effect and erosion of the dielectric due to ionic bombardment. Figure 12 is an example of the puncture failure. Before the RF power failures occur in the cable there are other detrimental effects caused by the ionization of the air voids in the cable. Some of these effects are interference due to corona discharges, degradation of the dielectric strength and increase in the voltage standing wave ratio and attenuation of the transmission line. The only effect considered in this paper is the power handling capabilities of the cable with respect to frequency. Several investigators[6,7] have studied the power handling capabilities of RF cables. However, the frequency range has been from 60 Hz to a few KHz. It is believed that experimental data on the frequency effect on RF cables in MHz or GHz frequency range is not available. It is generally accepted that the higher the frequency of CW the lower the voltage breakdown and the shorter the life of the cable. However, with pulse power, according to J. H. Mason[8] the number of discharges in an ionized air void depends on the voltage amplitude, but is nearly independent of the shape and duration of the pulse, because most of the discharges occur in the wave front. The breakdown strength of the dielectric is thus independent of pulse duration and therefore of frequency.

MATERIALS

The cables used in this investigation were chosen to represent a cross-section of the commercially available radio frequency cables, over a range of diameters. Small, medium and large diameter cables were represented by type RG-58C/U, RG-214/U and RG-218/U, respectively and their equivalents employing silicone and polytetrafluoroethylene. The physical properties of these cables are shown in Table 1.

EXPERIMENT

Conduct of the experiment presented two basic problems (1) determination of the inner conductor temperature while the cable is energized, and (2) application of the required RF power to the input of the cable under test. The criterion for maximum power handling capability of the cable is based on the maximum allowable surface temperature of the cable inner conductor. Determination of the inner conductor temperature during the power test was not feasible so an analysis was undertaken both theoretically and experimentally to determine the thermal characteristics of each cable. The temperature of the inner conductor was determined indirectly by measuring the cable jacket temperature and applying the heat transfer characteristics of the specific cable under test to these measured temperatures.

Since the test parameters, such as power input, ambient temperature and altitude were maintained constant until the full thermal stabilization of the cable was realized before a test step was considered complete, the steady state equations describing the heat transfer could be considered applicable. Utilizing these equations, a theoretical analysis of the thermal characteristics of a cable was made and a digital computer program was written to calculate the temperature of each interfacing layer of each cable. These temperatures were calculated as a function of ambient temperature and pressure (altitude) for the chosen limiting inner conductor temperatures.

In addition to the aforementioned temperature calculations, experimental data was generated both to increase the level of confidence in the mathematical model and to make refinements to the calculations where limited data on the thermal and radiation parameters was available or where engineering estimates had to be made to perform the calculations.

The experimental data was obtained by energizing a specimen or a model of each cable with a known direct current and observing the change in resistance of the inner conductor while monitoring the resultant temperature levels with thermocouples at various cable material inter-

TABLE 1

PHYSICAL PROPERTIES OF CABLES TESTED

Type	Inner Conductor	Dielectric	Outer Conductor	Jacket
RG-58C/U	19/0.0071" Tinned Copper strands	OD-0.116", solid Polyethylene	Single Braid Tinned Copper	Type IIA
RG-214/U	7/0.0296" Silver covered Copper strands	OD-0.285" solid Polyethylene	Double Braids Silver Covered Copper	Type IIA
RG-218/U	0.195" solid bare copper	OD-0.680" solid polyethylene	Single Braid Bare Copper	Type IIA
RG-180B/U	7/0.0040" Silver plated Copperweld strands	OD-0.102" solid Polytetrafluoroethylene	Single Braid Silver Covered Copper	Type IX
RG-142B/U	0.0390" Silver Plated Copperweld, solid	OD-0.116" solid Polytetrafluoroethylene	Double Braids Silver Covered Copper	Type IX
RG-225A/U	7/0.0312" Silver plated Copper Strands	OD-0.285" solid Polytetrafluoroethylene	Double Braids Silver Covered Copper	Type V
RG-117A/U	0.188" Solid Bare Copper	OD-0.620" solid Polytetrafluoroethylene	Single Braid Bare Copper	Type V
RG-296/U	37/0.336" Silver covered Copper Strands	OD-0.906" Silicone Rubber	Single Braid Tinned Copper	Polychloroprene, Extruded
RG-122/U (Silicone equiv)	7/0.0063" Silver covered Copperweld Strands	OD-0.083" Silicone Rubber	Single Braid Tinned Copper	Chlorosulfonated Polyethylene, Extruded
RG-214/U (Silicone equiv)	0.0201" solid Silver Covered Copperweld	OD-0.195" Silicone Rubber	Single Braid Tinned Copper	Chlorosulfonated Polyethylene, Extruded

faces. The temperature of the inner conductor was calculated from the resultant changes of inner conductor resistance. Measurements were made at multiple ambient temperatures and altitudes. The inner conductor maximum temperature limits used for polyethylene, polytetrafluoroethylene and silicone insulated cables were 176°F, 400°F and 300°F, respectively. Further experimental data was obtained by energizing the cables with an RF signal. The signal level was increased gradually, with the samples mechanically stressed to produce displacement of the inner conductor when thermal deterioration of the dielectric was realized. The inner conductor displacement was detected with a time domain reflectometer. The information was also used in adjusting the computed jacket temperatures to take into account the thermal contribution due to the dielectric and outer conductor losses.

Initial planning called for the design and fabrication of environmental chamber RF feedthroughs having electrical properties commensurate with the planned test frequencies and anticipated power levels. The feedthroughs were also intended to provide thermal isolation of the test cables from the chamber walls and from the external environment. A more detailed analysis, however, following the final determination of test cable types led to the rather definite conclusion that any practical feedthrough which incorporated a connector interface with the test cable would be susceptible to failure at that interface prior to achieving the power limitation of the test cable, or would have to be of a dimensional configuration which would impose upper frequency limitations substantially below the upper frequency rating of the test cable.

Alternate approaches which were investigated identified the most feasible method as being the use of the actual test cable as the means of entry and exit from the environmental chamber.

Tests were conducted on a variety of cable types and sizes simulating the feedthrough section of the test cables to determine the nature of the "heat sinking" effect and to define the distance within the environmental chamber where this effect could be neglected. These tests were conducted by artificially (non-RF) heating the sample center conductor and monitoring center conductor, dielectric, outer conductor and jacket temperatures along the length of the sample. This was accomplished at representative temperatures and altitudes distributed over the intended test ranges. The actual test cables were configured to a length which, in addition to providing chamber entry and exit, resulted in the desired length of cable suspended along the centerline of the chamber. The measured input power levels were then corrected to compensate for cable loss to the location where "heat sinking" could be neglected.

Another problem which became apparent early in the program was that the output fittings of most of the RF power sources were waveguide and none of the available waveguide to coaxial adapters - - even those developed for high power Electronic Counter Measure (ECM) systems - - would withstand the anticipated test power levels. The solution of the problem was the design and fabrication of special transitions which accommodated the test cable entry into the waveguide without the use of intervening coaxial connectors. A series of these transitions was developed in the waveguide sizes required to cover the test frequencies and was used to terminate the test cables at both input and output (waveguide loads) ends. The transitions were further sophisticated to provide a feature wherein the coaxial half of the transition of any particular cable would "plug-in" to any of the waveguide sizes thereby eliminating the need to disturb the cable braid terminating mechanism when changing test frequency. The reflection coefficients of the transitions were a best compromise considering all of the cable sizes and in most cases were less than 1.5:1 VSWR without tuning. For a few of the frequency-cable-size combinations, however, waveguide E-H tuners were used to reduce VSWR. To further enhance the breakdown withstanding characteristics of the transitions for the pulse power testing they were pressurized to approximately 25 psig using Freon 12. A plot showing the relative breakdown values for dry air and Freon 12 versus pressure is shown in Figure 4.

The design philosophy for the transitions was merely to transfer the RF energy from the waveguide TE_{10} mode to the coaxial TEM mode in the smoothest possible manner without creating any areas of undue

voltage concentration in the process. A configuration commonly referred to as a "door knob" transition backed by a waveguide short circuit was selected and optimized for reflection coefficient over the range of frequencies and cable sizes of interest. The unique feature of the transitions is that the cables actually "plug in" to the waveguide, with the cable dielectric engaging the surface area of the door knob surrounding the cable center conductor contact. A typical transition and several associated cable terminations are shown in Figure 5. A typical cutaway drawing is shown in Figure 6.

Two basic types of RF power tests were accomplished: (1) CW tests to determine the cables power handling capability as limited by heating due to conductor and dielectric losses, and (2) low duty cycle pulse tests to determine the RF voltage breakdown capability of the cables. The testing was accomplished at several frequencies over the operating range of the test cables to provide the data points which were the basis for the resultant power capability versus frequency curves. The tests were repeated at sufficient temperature and altitude conditions to determine the dependency of power rating on these factors.

The tests were conducted by installing the test cable in a temperature-altitude chamber and instrumenting the length of the cable with 22 thermocouples. Thermocouple spacing was every six inches starting at the cable input for the first eight feet with the remaining thermocouples distributed uniformly over the remainder of the cable. Test cables were approximately 14 feet in length. A typical chamber and thermocouple installation is shown in Figure 7. An overall view of a typical test is shown in Figure 8. Entry and exit from the test chamber was accomplished by means of the test cable as previously discussed. Both the input and output ends of the test cable were terminated in specially designed cable-to-waveguide transitions which were in turn connected to the RF power source or a high power waveguide termination through calibrated power monitoring directional couplers and power meters. Input forward and reflected power, output forward power, test sample thermocouple readings and test chamber temperature and pressure were monitored and recorded throughout each test. A schematic diagram showing a typical test setup is shown in Figure 9.

The detailed test sequence consisted of installing and instrumenting the test cable in the test chamber and establishing the desired chamber altitude and temperature condition. The cable was then allowed to "soak" under these conditions until temperature stabilization at the desired temperature was accomplished. The chamber was maintained at these conditions for the remainder of the test. RF power was applied to the input of the test cable in small increasing steps until the cable jacket temperature stabilized at the predetermined limiting temperature. This process was then repeated for all scheduled temperature and altitude conditions and for each additional test frequency.

The CW cables were visually examined before and after the entire test sequence and VSWR and Time Domain Reflectometer tests were conducted before and after the power tests at each test frequency to check for cable deterioration. After all testing was completed on a particular sample, segments were dissected and the dimensions and condition of cable members were determined by inspection and deterioration or changes noted.

RF pulse tests were conducted on different cable samples from those subjected to the CW tests. The pulse test samples were visually inspected and VSWR and Corona ignition and extinction tests were conducted prior to applying RF power. The actual conduct of the tests was very similar to the CW tests except that jacket temperatures were monitored for information and as a "not-to-be-exceeded" parameter. Peak power was increased slowly until the sample failed by dielectric breakdown. Sections of cable where breakdown occurred were carefully examined and conditions noted. Sections of cable which were not catastrophically involved in the breakdown were inspected to ascertain less severe deterioration. Photographs of cable sections where breakdown occurred are shown in Figures 10 through 14.

RESULTS

CW Power Tests

Curves of CW Power Handling capability versus frequency for the Teflon and

Polyethylene cable types tested are shown in Figures 15 through 23. These curves have been derated thirty percent below the actual test data points to accommodate the effects of typical system installations (i.e. bends, clamps, thermally insulated sections, etc.). The curves are plotted for a range of ambient temperatures and altitudes which correspond generally to the practical environmental operating range of the associated cable. Derating factors to account for VSWR values greater than 1.0 are shown in Figure 31. Information as to the rating of a cable at an intermediate environment may be determined by interpolation using the derating curves for altitude and ambient temperature given in Figures 32, 33, and 34.

Examination of predicted RF performance characteristics of the selected silicone cable indicated their practical operating frequency range to be confined to rather low frequencies. The initial series of CW tests on all three cable types supported the accuracy of these predictions. The cables become extremely lossy as frequency is increased above the HF range. They are essentially useless for the transmission of RF energy over most of the frequency range covered by this program.

A detailed examination of the materials used in these test cables revealed the primary contributor to loss was the silicone rubber dielectric. The magnitude of this dielectric loss does not remain constant versus frequency or temperature nor does it vary in a manner characteristic of most microwave dielectrics. Contacts with the cable supplier and subsequent information obtained from the silicone rubber supplier indicated a large dependency on RF frequency and temperature. Depending on the particular compound used, the dielectric loss tangent may increase by a factor of 5^9 with increasing frequency between 1 MHz and 10 GHz and may decrease by a similar factor with increasing temperature from 25°C to 200°C. Dielectric constant also undergoes a significant change as a function of temperature with the result that cable characteristic impedance is temperature sensitive. In addition, these variables are interrelated in a rather complicated manner and for a particular chemical compound are dependent upon the exact process (cure temperature, cure time, etc.) used during the fabrication of the cable.

Attenuation measurements made at low power levels over a wide frequency range and under various temperature conditions confirmed the loss peculiarities as described above although the actual high power situation wherein a variation of dielectric temperature across the diameter of the dielectric could not be simulated. Plots of these attenuation measurements are shown in Figures 24, 25, and 26.

A second series of high power tests was conducted. The set of CW power rating curves based on these retests are shown in Figures 27 through 29.

Peak Power (Voltage Breakdown) Tests

Pulse power tests conducted on the ten cable types over the frequency and ambient environment ranges used for the CW tests revealed the breakdown power levels to be generally insensitive to frequency, to ambient temperature and to altitude within the operating ranges of the cables. The only exception was the Teflon dielectric cables which exhibited a marked decrease in breakdown power level at higher ambient temperatures. A search of available literature[10] on the properties of Teflon revealed that (Polytetrafluoroethylene) undergoes a significant change (step function decrease) in dielectric strength of about 25 percent as temperature is increased above approximately 100°F. These relative voltage levels correspond favorably with breakdown power levels experienced on RG-225/U samples which had similar corona extinction voltage levels but were power tested at room ambient temperature and at elevated temperatures.

A review of the characteristics of known categories of electronic systems which might be expected to approach the peak power ratings of the Teflon cables tested revealed that average power heating would raise the cable center conductor temperature to the region where the lower power (higher temperature) rating would apply. For this reason the recommended maximum peak power ratings for Teflon cables are with respect to this lower value.

A considerable variation in corona extinction voltage was noted in samples

taken from adjacent locations on the procured lengths of cable - the largest variation being approximately 25 percent in RG-225/U samples. The RF breakdown power levels for samples exhibiting this difference in corona extinction values, varied by approximately 50 percent - the lower corona value corresponding to the lower breakdown level.

The available samples of RG-122/U (silicone equivalent) cable possessed a mechanical condition wherein the cable center conductor exhibited periodic "kinks" resulting in a center conductor offset with respect to the centerline of the dielectric approximately every six to eight inches along its length. The offset was approximately equal to the diameter of the center conductor. As would be expected, RF breakdown occurred at these points. The breakdown level for this type of cable if properly constructed would undoubtedly be higher than the values observed. Table 2 shows the derated values of maximum power level suggested for the ten cables tested. The tabulated values were obtained by derating the actual test breakdown power level values by 25 to 50 percent to take into account the differences between the long and short term breakdown properties of the dielectric involved, and the variations in the corona extinction values of the tested samples relative to the required minimum values specified in MIL-C-17D.

TABLE 2

Maximum Recommended Pulse Power Ratings

Cable Type	Maximum Recommended Peak Power (Watts x 10^6) VSWR=1.0:1
RG 58C/U	.08
RG 214/U	.25
RG 218/U	2.50
RG 180B/U	.08
RG 142B/U	.30
RG 225A/U	.35
RG 117A/U	4.0
RG 122/U Silicone Equivalent	.10
RG 214/U Silicone Equivalent	.20
RG 296/U	3.0

DISCUSSION

The suggested maximum power ratings provided by Figures 15 through 23, 27 through 29, and by Table 2 are based on a VSWR of unity and on the temperature and altitude conditions as noted. Corrections to account for other conditions may be determined as discussed below.

The pulse power rating of a cable based on a 1:1 VSWR must be decreased if a higher voltage standing wave exists on the cable. The magnitude of this necessary derating can be determined by the expression $\frac{1}{VSWR}$. Figure 30 shows percent derating versus VSWR and can be applied directly to the ratings given in Table 2.

The CW power rating of a cable is also affected by voltage standing wave ratio, or rather by the associated power standing wave. In this case the relation is more complicated since it involves not only the magnitude of the standing wave but also the thermal characteristics of the cable and physical spacing between the power standing wave peaks. For solid dielectric cables of the types considered by this paper the thermal characteristics are predominantly determined by cable diameter. The spacing between power maximums is determined by frequency. The magnitude of this necessary CW derating can be calculated from the expression $\frac{2\ (VSWR)}{(VSWR)^2 + 1 + K\ ((VSWR)^2 - 1)}$ where K is a factor which considers cable characteristics and frequency. Figure 31 shows percent derating versus frequency for VSWR values from 1.0 to 3.0 and can be applied directly to the curves of Figures 15 through 23 and 27 through 29.

The Pulse power ratings of Table 2 are based entirely on voltage breakdown limitations whereas the CW ratings are determined by allowable cable temperature. Both limitations must be recognized when choosing a cable for a particular application. This selection can be accomplished quite simply by first determining that the operating pulse power level, properly derated for system VSWR, will not exceed the value for the cable being considered (Table 2). The required average power level is then determined from system pulse

level and duty cycle and checked against the candidate cable CW rating curve which has been properly derated for system VSWR and operating environment.

The Pulse power test results indicate the RF voltage breakdown capability of the cable types tested to be fairly insensitive to environmental conditions with the exception of the temperature dependency of polytetrafluoroethylene. This obviously is not true in the case of CW or average power handling. Curves plotted in Figures 15 through 23 show CW power handling ratings for nominal (sea-level - 86^{O}F) and limiting environmental conditions. The rating for any intermediate environment may be obtained by referring to Figure 32 for the appropriate altitude derating factor and to Figures 33 or 34 for the proper temperature modifying factor. These corrections are then applied to the sea level 86^{O}F power rating curve (Figures 15 or 19) for the cable type under consideration.

It is believed that the information contained in this paper facilitates the selection of the most suitable RF cables for high frequency power systems with greater certainty. However, the transmission line design would not be complete without the selection of the appropriate connectors.

Although not a part of this paper, it should be recognized that the connectors required in a practical transmission line installation will usually impose a peak power limit and may impose a CW limit significantly below that of the associated cable. To complete a total transmission system design, the designer must have knowledge of the power handling capability of the intended connectors. I appeal to those interested on this subject to make a similar investigation to determine RF power ratings for the commonly used connector series.

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Mr. G. Rodriguez received his BSEE degree in 1950 from the Indiana Institute of Technology in Fort Wayne, Indiana. He was associated with the Physical Science Division of the U. S. Naval Applied Science Laboratory from 1951 to 1969 in the capacity of project engineer on research and development of RF transmission lines. In 1969 he was transferred to the Electrical Division of the Annapolis Laboratory of the Naval Ship Research and Development Center, Annapolis, Maryland. As senior project engineer in this activity, he is in charge of the Radio Frequency Measurements Group.

Mr. Rodriguez is a member of IEEE, Leader of Group B, RF Measurements American National Standard Institute Committee C-83.3. He has served as U. S. delegate of the International Electrotechnical Commission (IEC) Sub-Committees SC-46A, SC-46B and SC-46D and recently has been appointed U. S. Chief delegate of IEC Sub-Committee SC-46D.

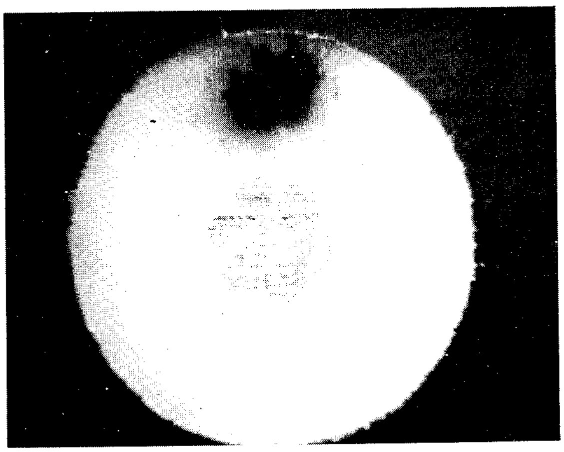


FIG. 1 RG-225/U-12X GENERAL VIEW, PARTIAL DIELECTRIC BREAKDOWN

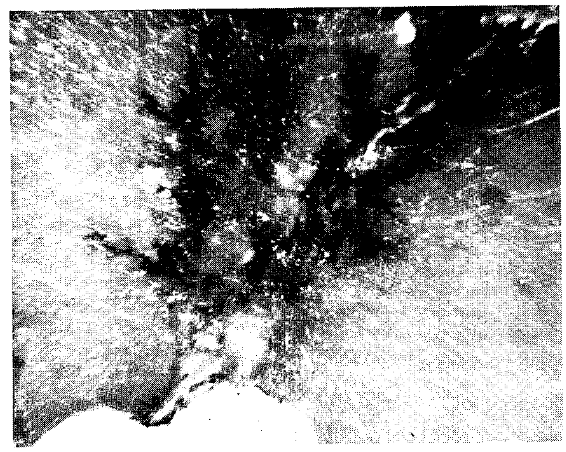
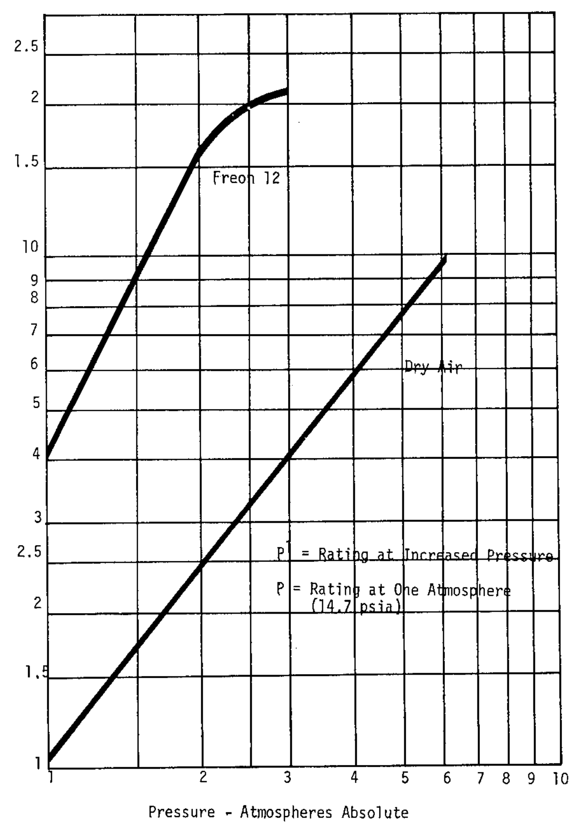


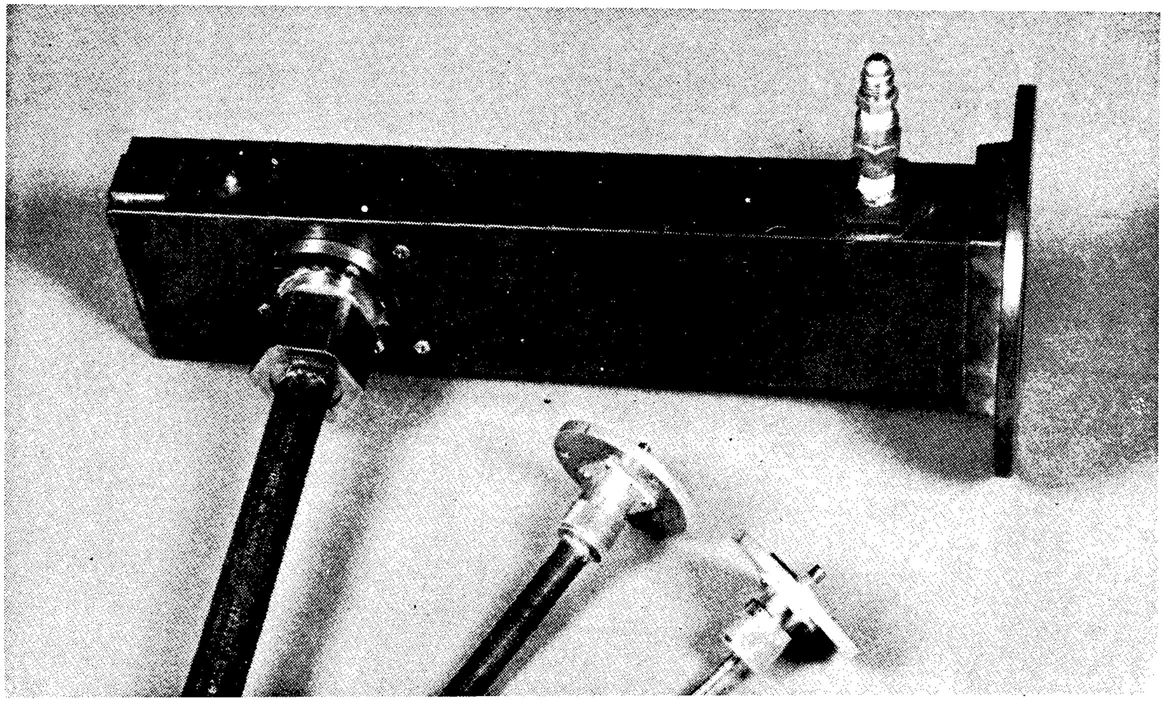
FIG. 3 CLOSE UP-RG-214/U,40X DIELECTRIC, INNER EDGE & TREEING

FIG. 2 RG-225/U-37.5X CLOSE UP OF DIELECTRIC-INNER EDGE, PARTIAL DIELECTRIC BREAKDOWN

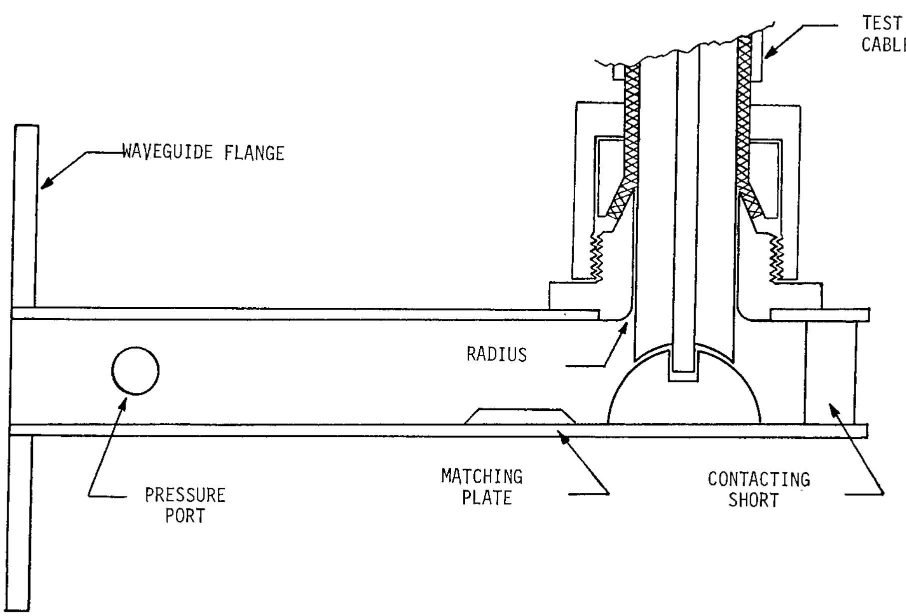


VARIATION OF PEAK POWER RATING WITH ABSOLUTE PRESSURE
DRY AIR VERSUS FREON 12

FIGURE 4

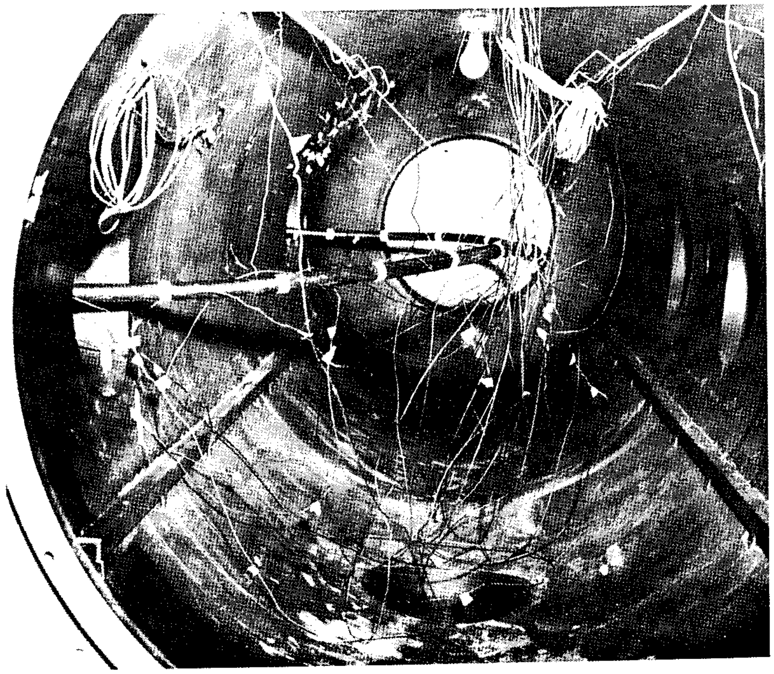


HIGH POWER WAVEGUIDE TO
CABLE TRANSITION
FIGURE 5

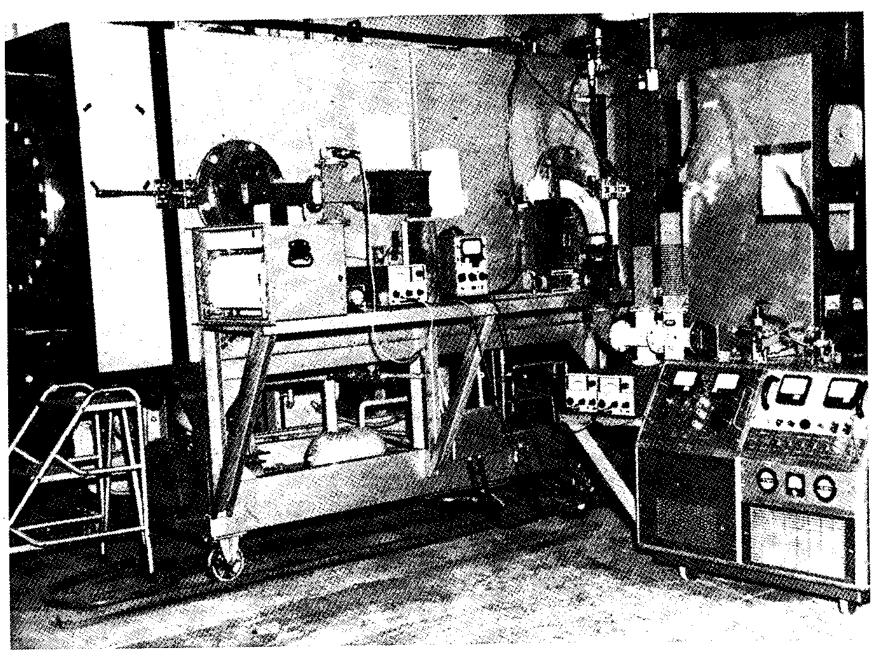


CONSTRUCTION SKETCH OF HIGH POWER
WAVEGUIDE TO CABLE TRANSITION

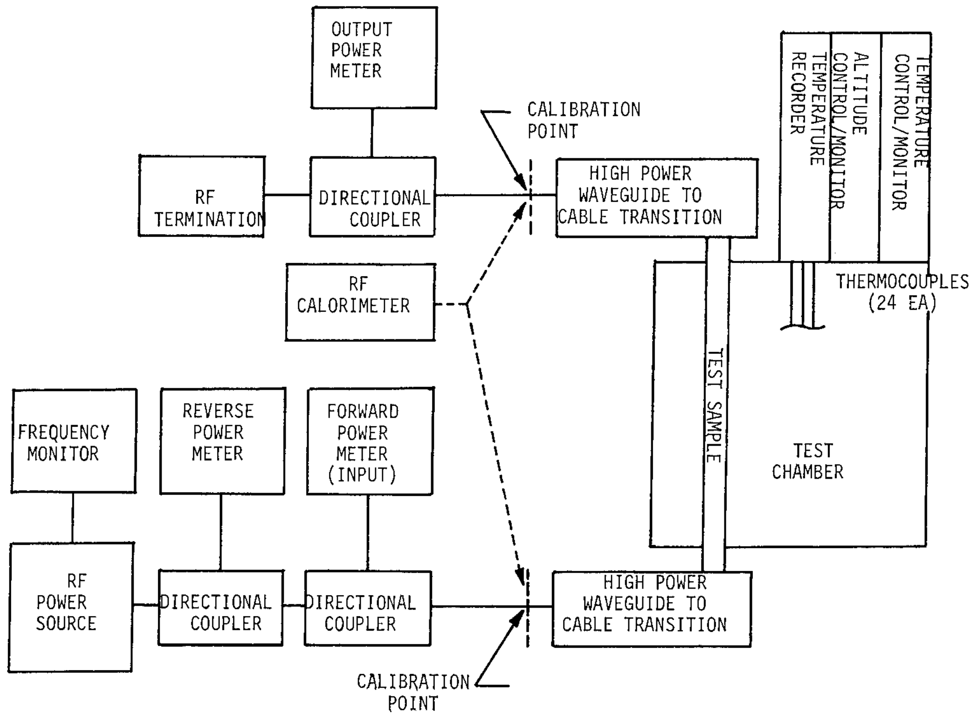
FIGURE 6



TYPICAL CHAMBER INSTALLATION,
RG-218/U INSTALLED
FIGURE 7



TYPICAL AVERAGE POWER TEST SETUP
FIGURE 8



SCHEMATIC DIAGRAM OF TYPICAL POWER TEST SETUP

FIGURE 9

FIG. 10 CLOSE UP-RG-214/U,30X DIELECTRIC, OUTER EDGE

FIG. 11 SILICONE RG-58/U-40X(EQUIV) CLOSE UP OF CRATER

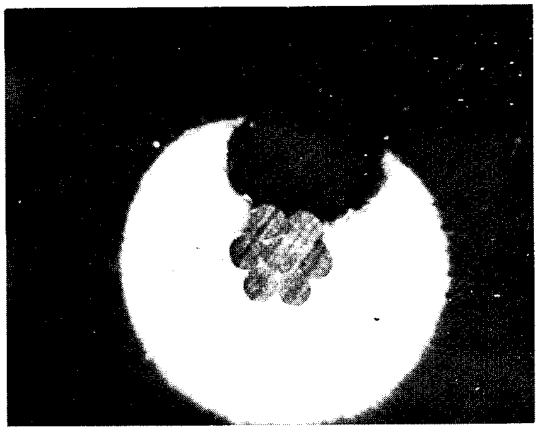


FIG. 12 RG-225/U-10X GENERAL VIEW, TOTAL DIELECTRIC BREAKDOWN

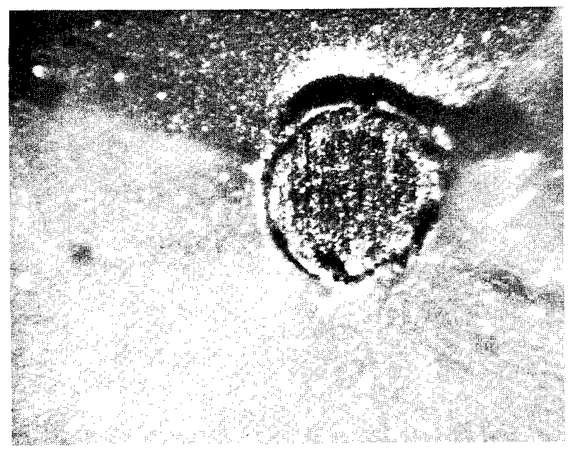


FIG. 13 SILICONE RG-58/U-70X(EQUIV) CLOSE UP TOTAL DIELECTRIC BREAKDOWN

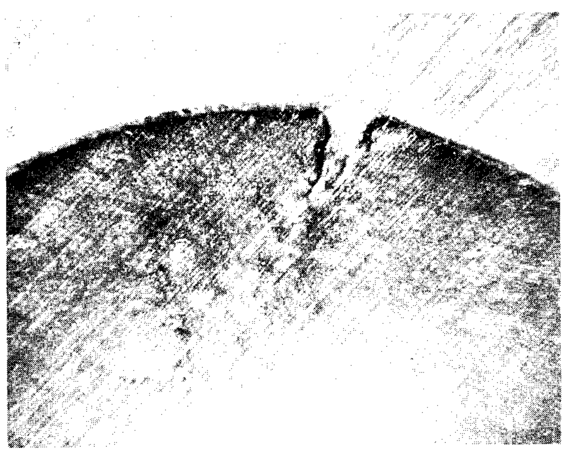
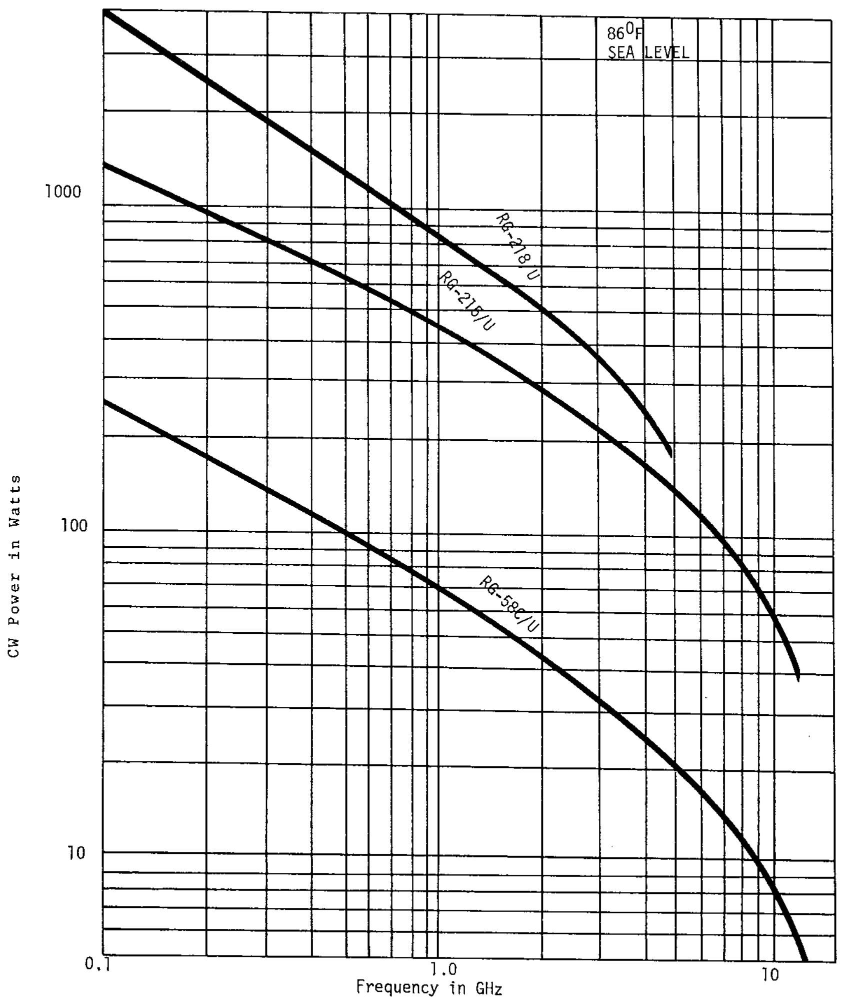
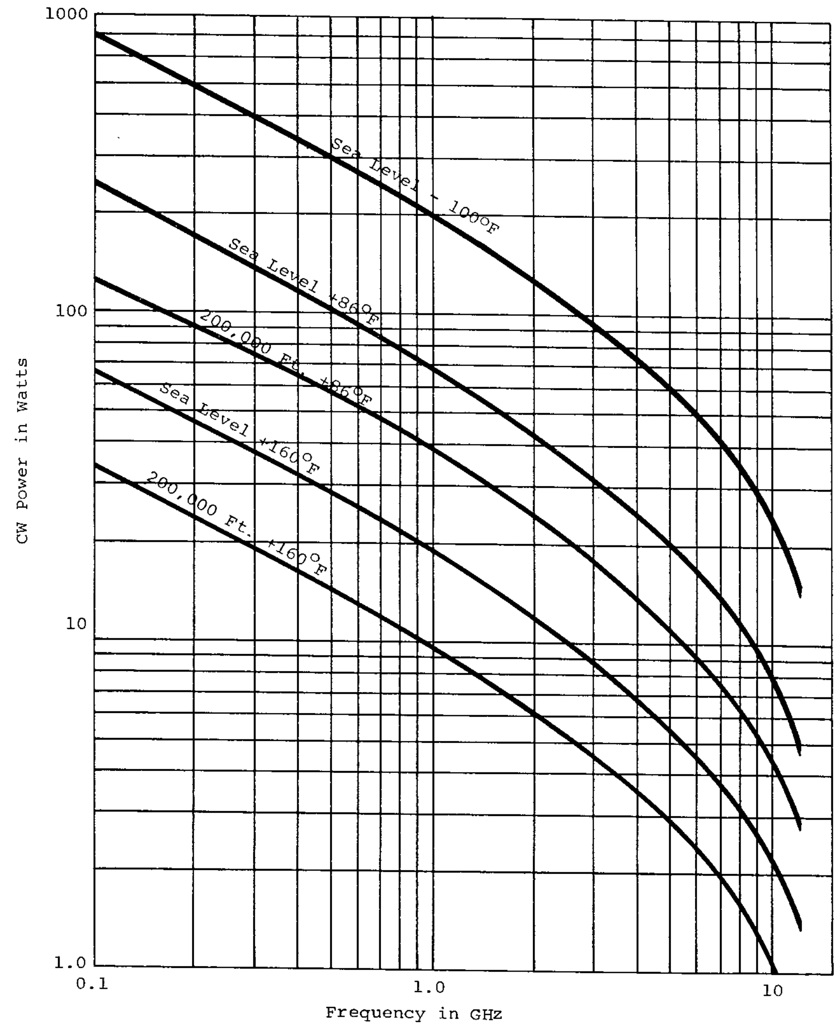


FIG. 14 CLOSE UP-RG-214/U,30Z DIELECTRIC, OUTER EDGE



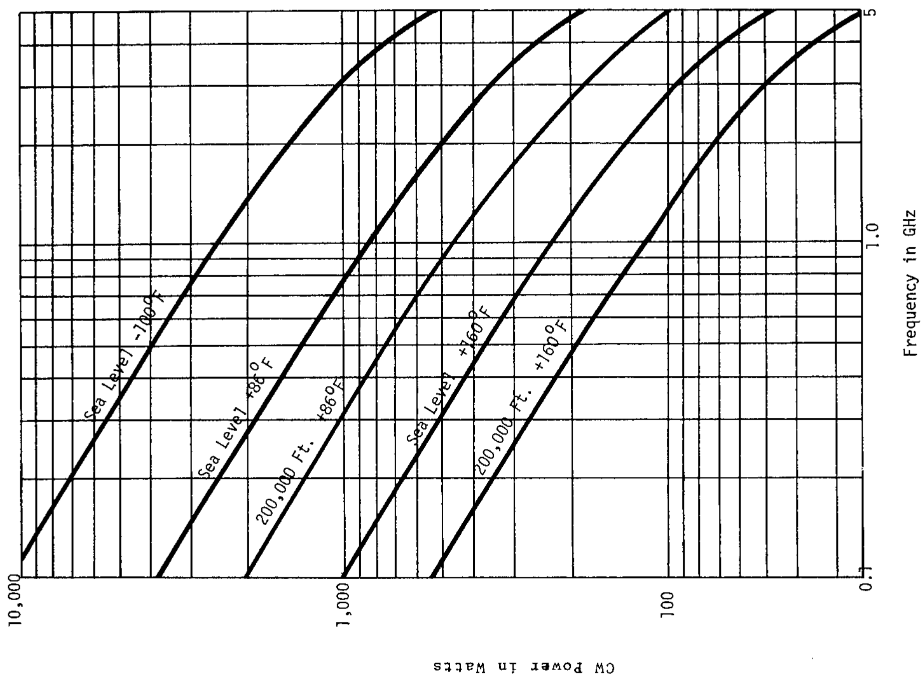
AVERAGE POWER RATING OF SELECTED
POLYETHYLENE DIELECTRIC CABLES

FIGURE 15



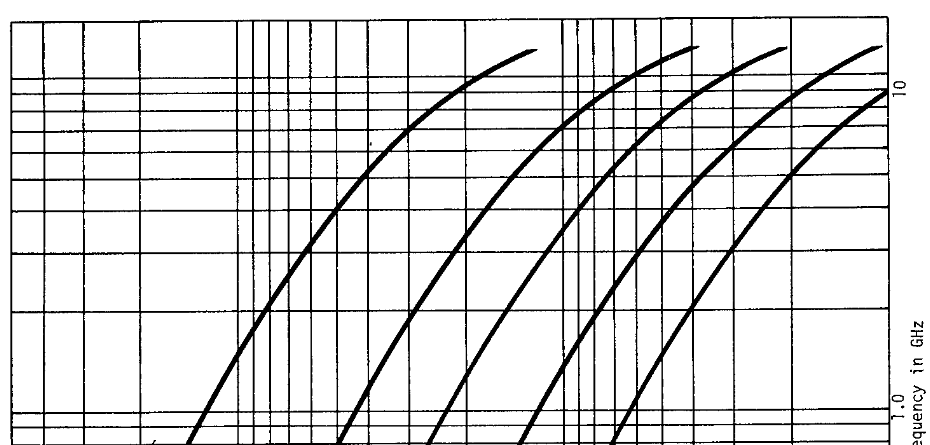
AVERAGE POWER RATING OF RG58C/U

FIGURE 16



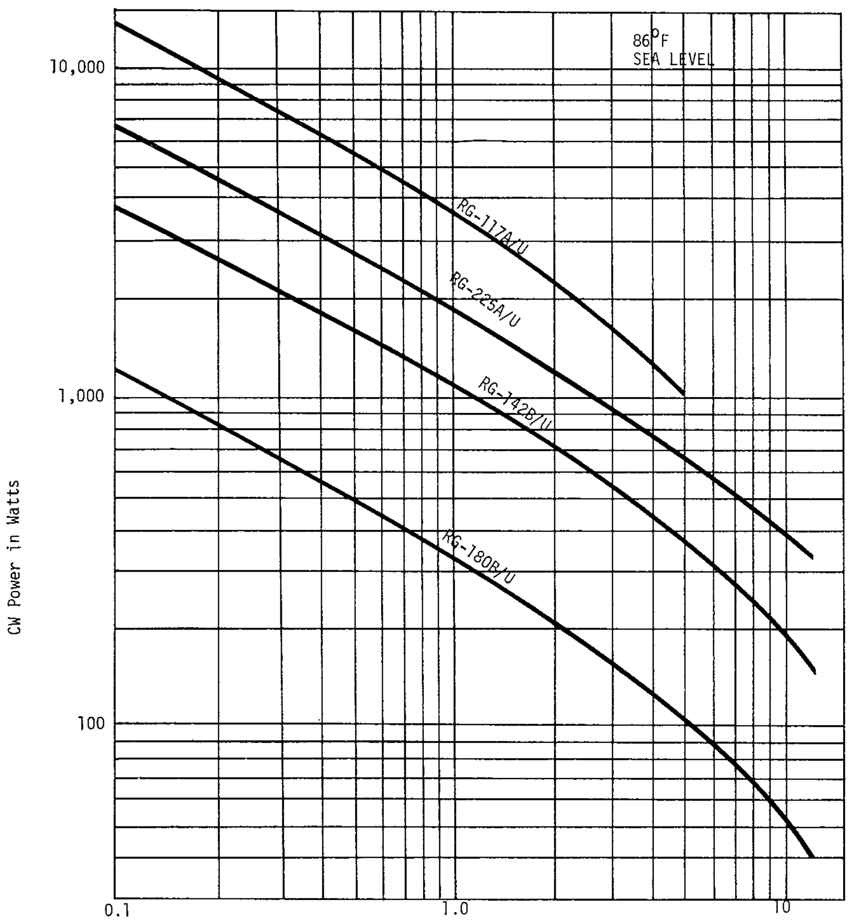
AVERAGE POWER RATING OF RG218/U

FIGURE 18



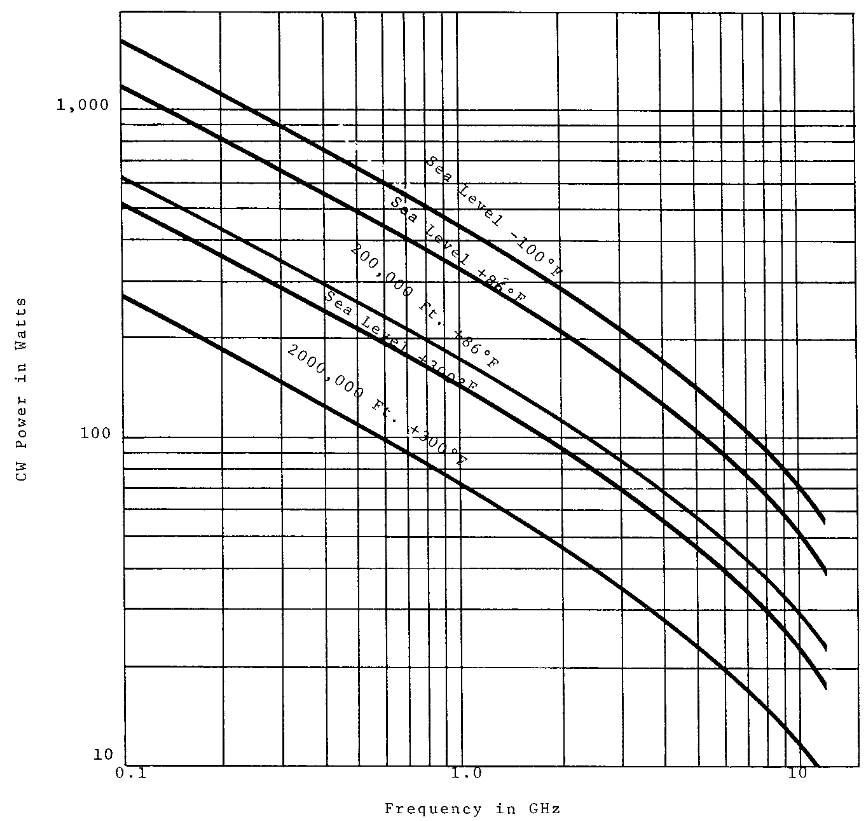
AVERAGE POWER RATING OF RG214/U

FIGURE 17



Frequency in GHz
AVERAGE POWER RATING OF SELECTED TEFLON DIELECTRIC CABLES

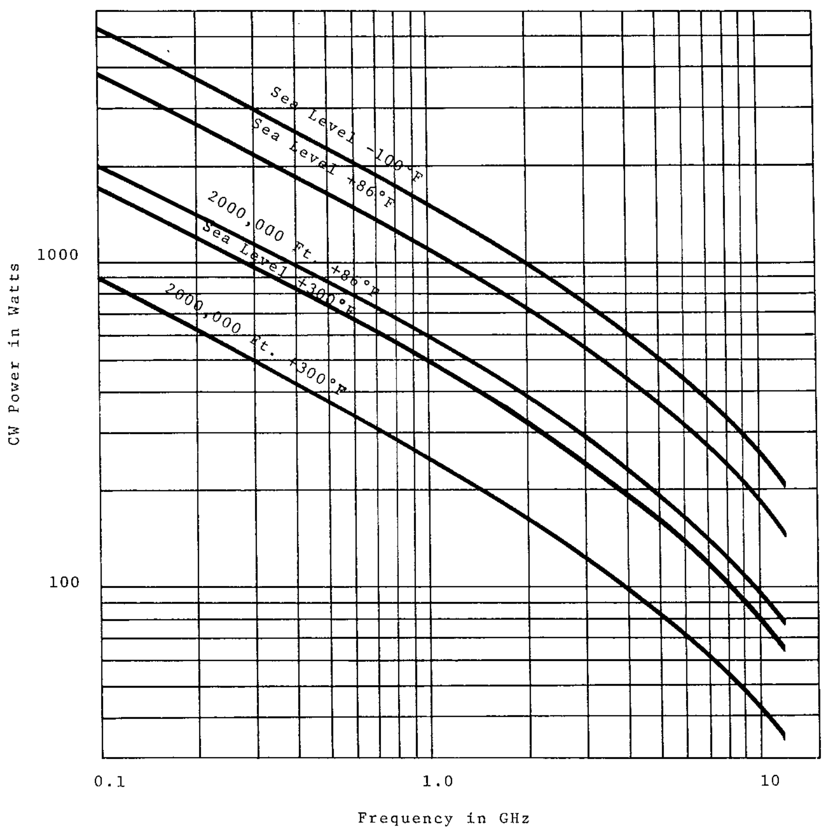
FIGURE 19



Frequency in GHz

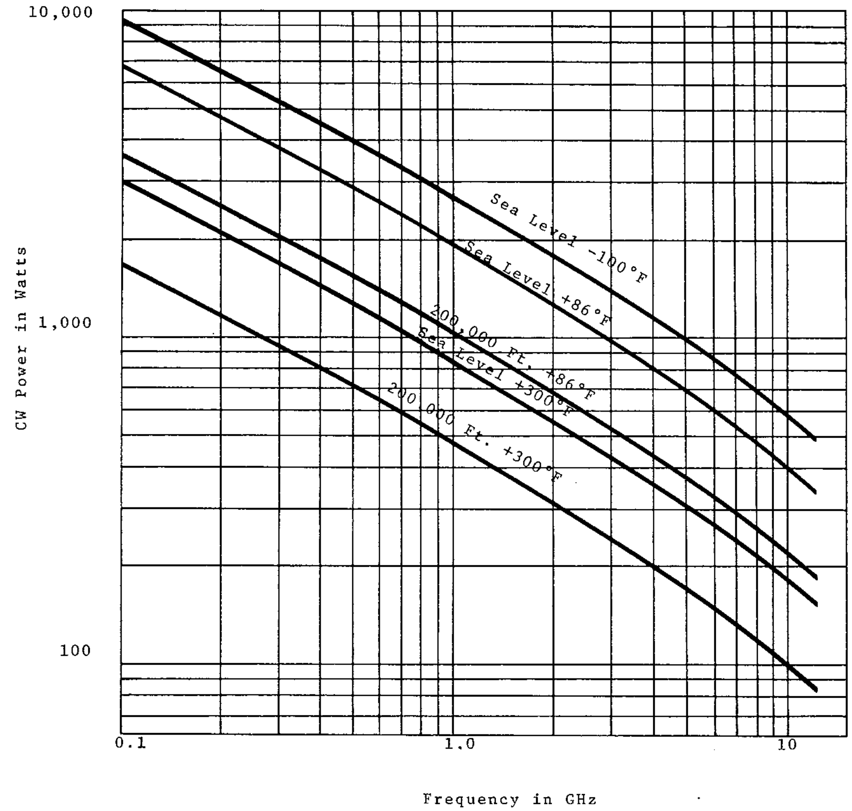
AVERAGE POWER RATING OF RG180B/U

FIGURE 20



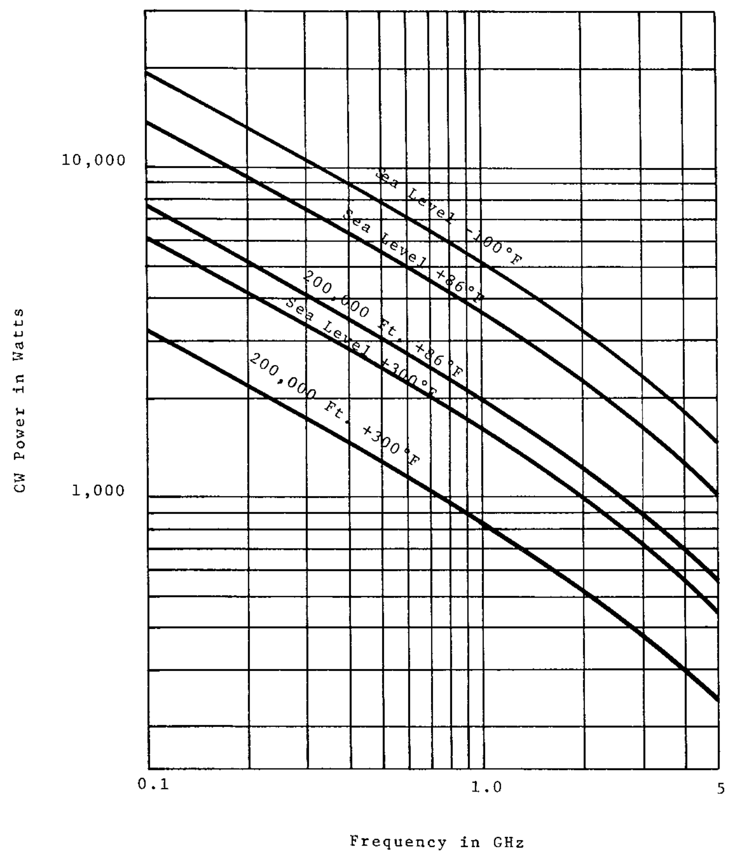
AVERAGE POWER RATING OF RG142B/U

FIGURE 21



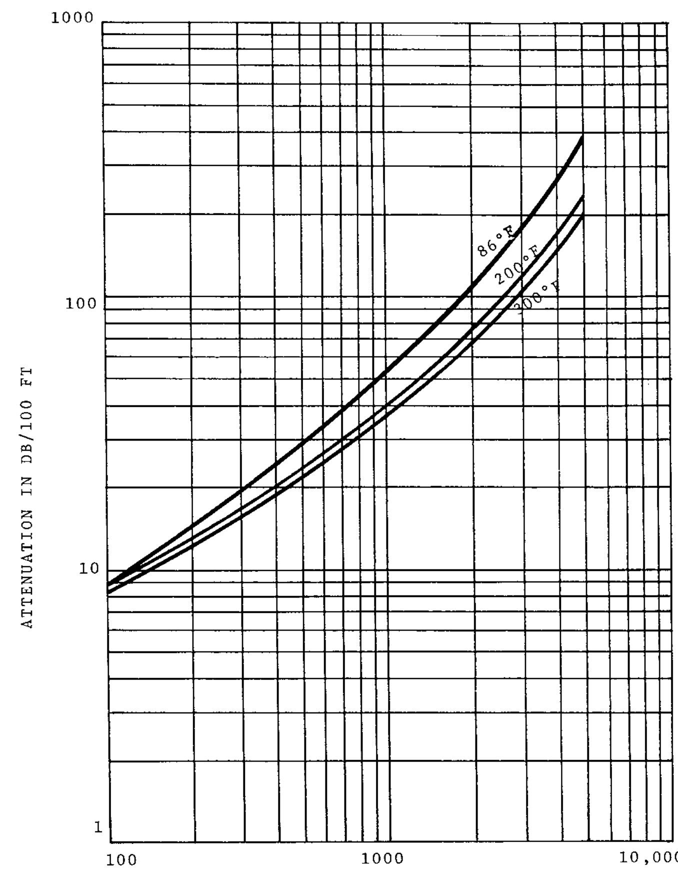
AVERAGE POWER RATING FOR RG225A/U

FIGURE 22

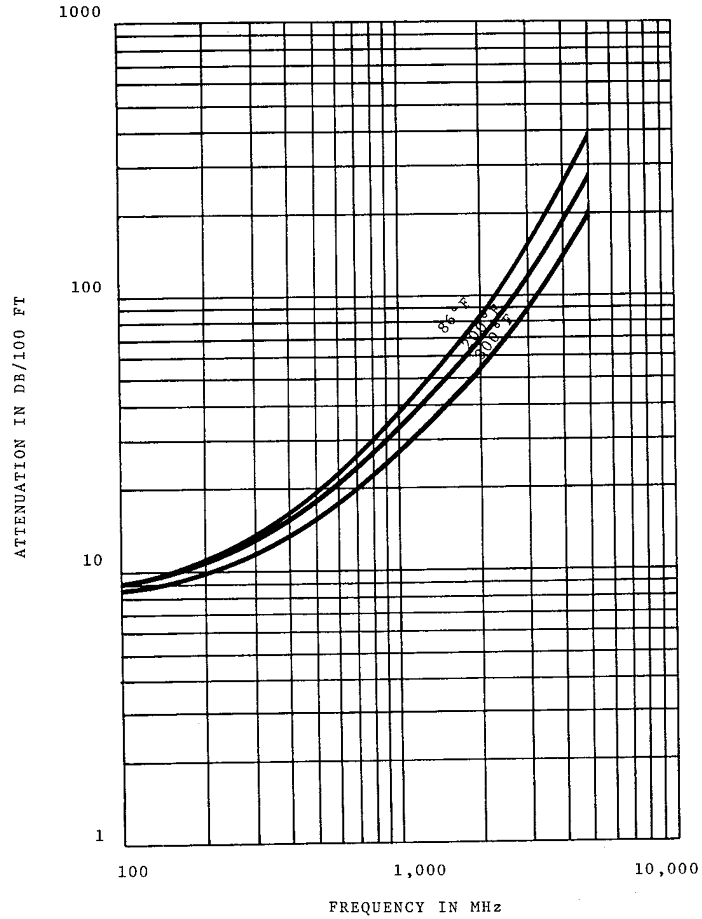


AVERAGE POWER RATING OF RG117A/U

FIGURE 23

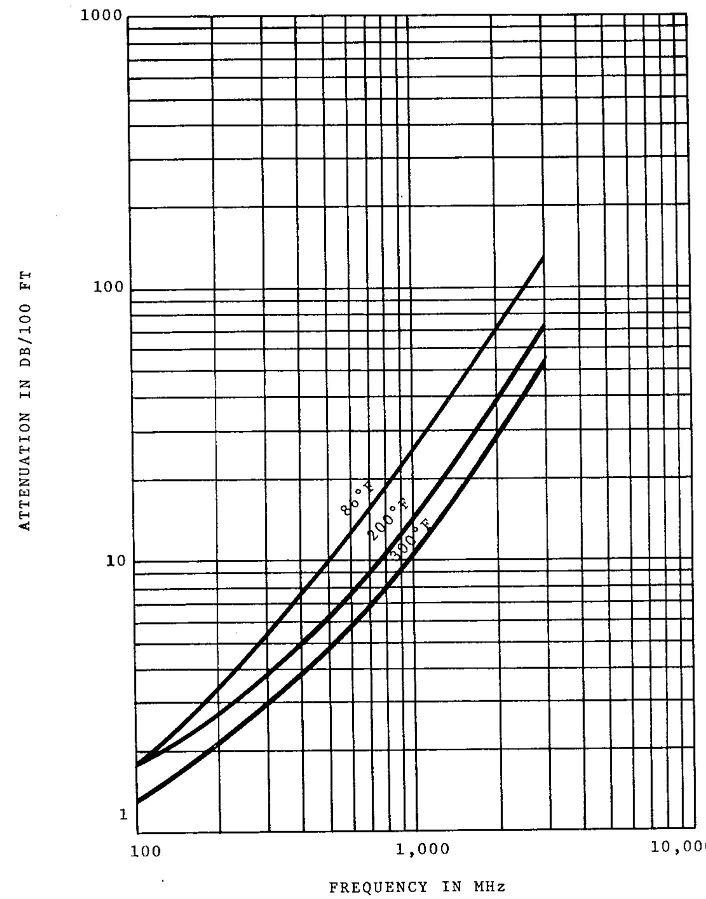


ATTENUATION VS FREQUENCY OF BIW-7870-C-G24
FIGURE 24



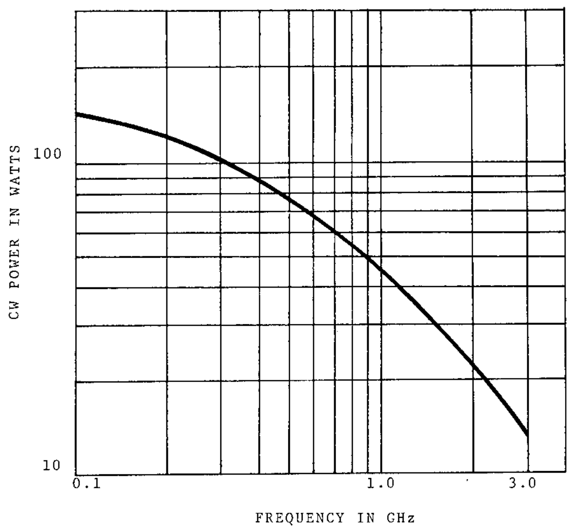
ATTENUATION VS FREQUENCY OF BIW-8482-C-G26

FIGURE 25



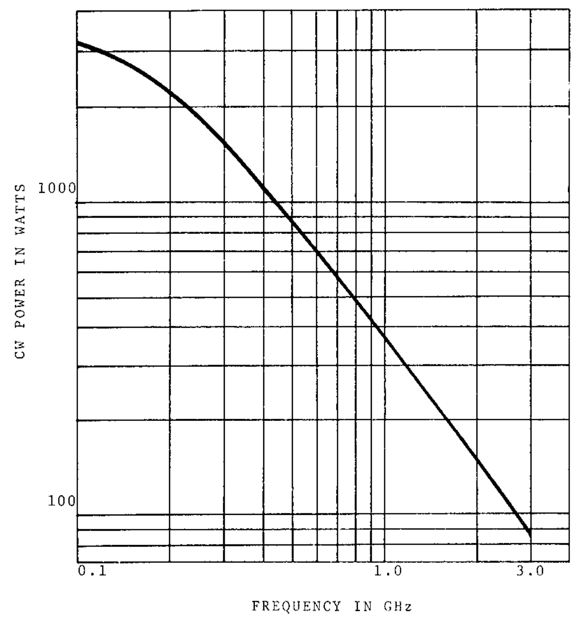
ATTENUATION VS FREQUENCY OF RG 296/U

FIGURE 26



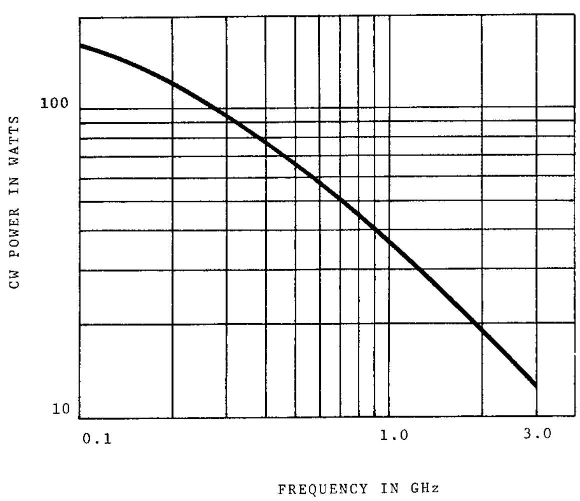
AVERAGE POWER RATING OF BIW-7870-C-G24

FIGURE 27



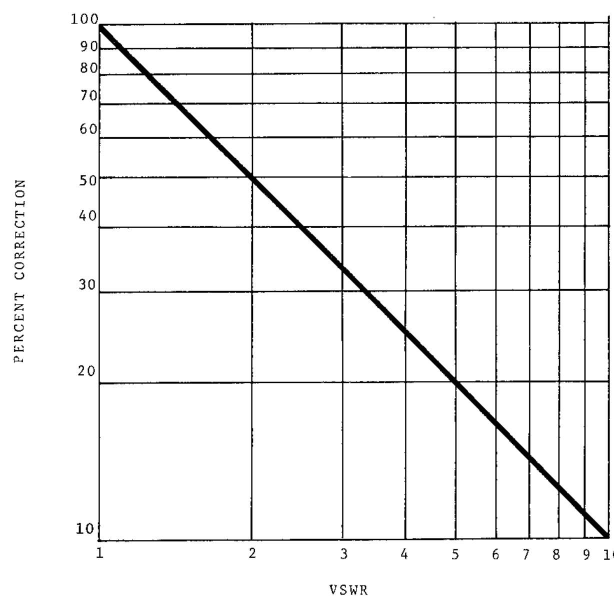
AVERAGE POWER RATINGS OF RG 296/U

FIGURE 29



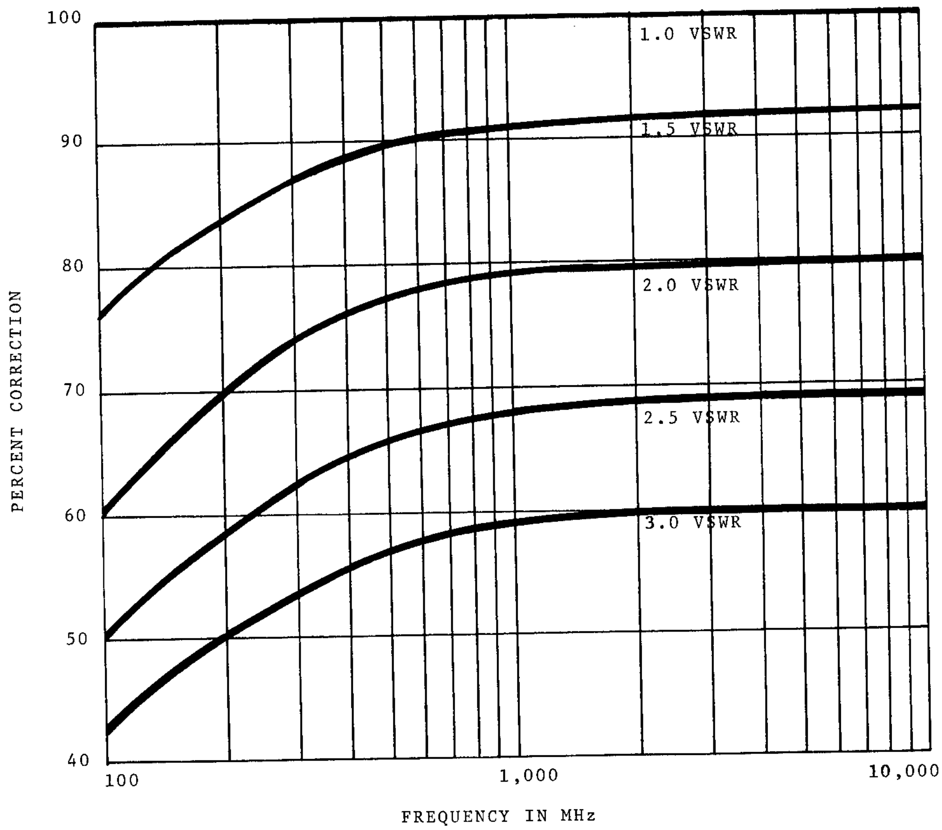
AVERAGE POWER RATINGS OF BIW-8482-CG26

FIGURE 28



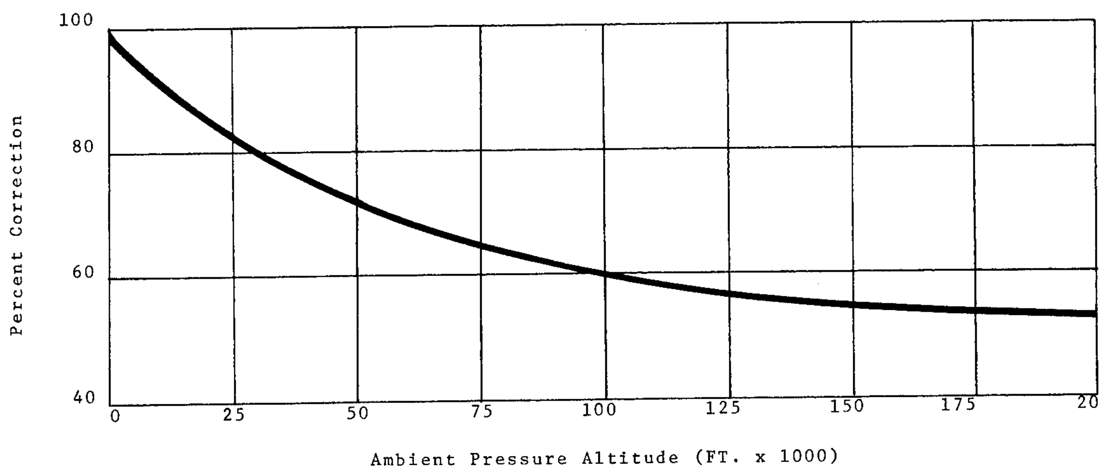
VSWR CORRECTION - PULSE POWER

FIGURE 30



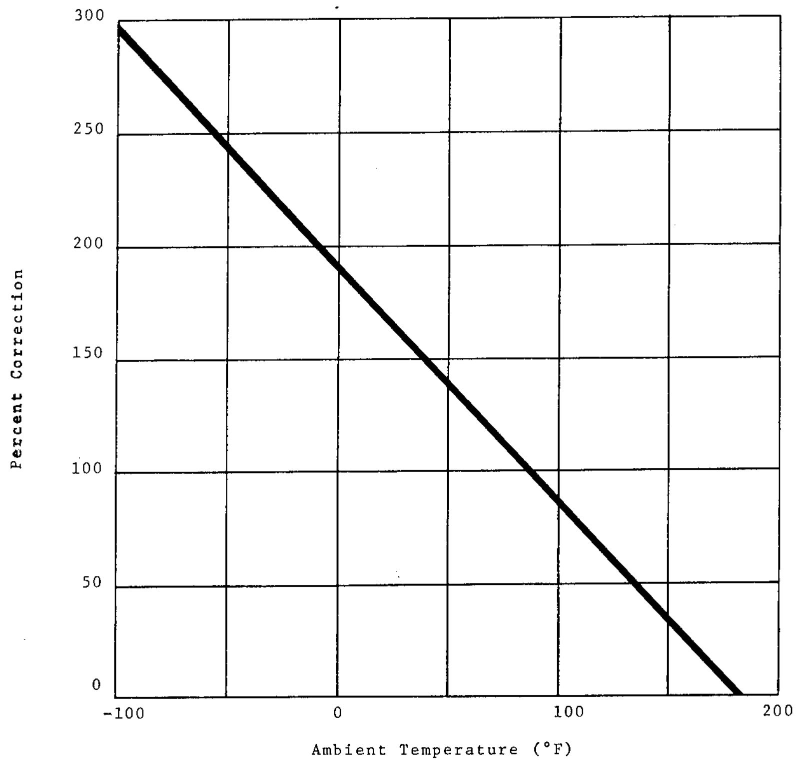
VSWR CORRECTION - AVERAGE POWER

FIGURE 31



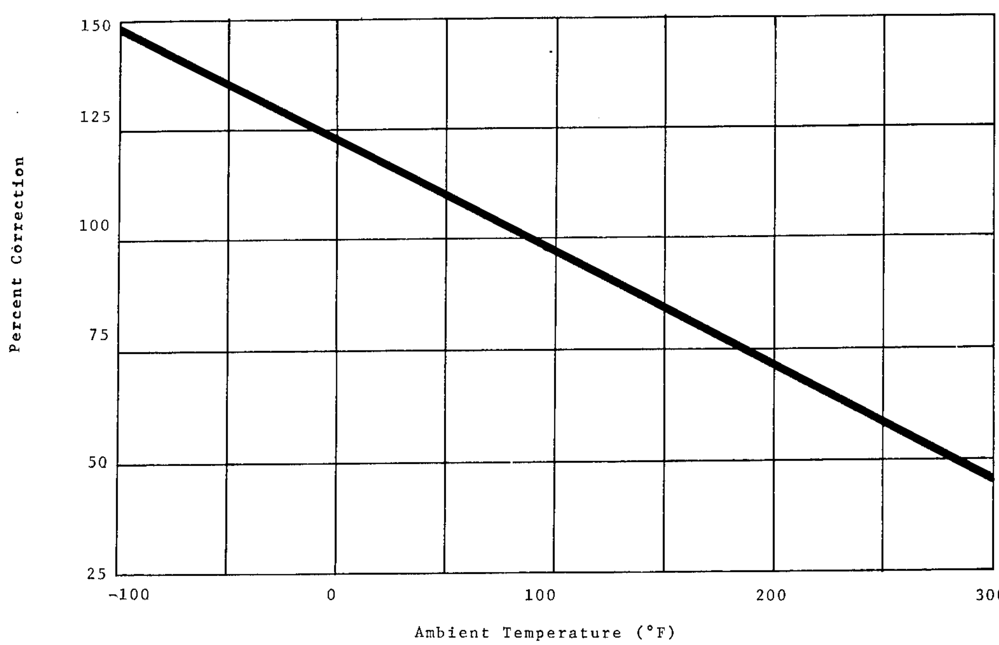
PRESSURE ALTITUDE CORRECTION

FIGURE 32



TEMPERATURE CORRECTION - POLYETHELENE DIELECTRIC

FIGURE 33



TEMPERATURE CORRECTION - TEFLON DIELECTRIC

FIGURE 34

THE EFFECT OF LIGHTNING ARCING CURRENTS ON TELEPHONE CABLES

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Rural Electrification Administration
Washington, D. C. 20250

Abstract

Data are presented on the effects of lightning currents arcing to various types and combinations of metal when applied as shield materials in telephone cables. These currents (18 to 83 kA in magnitude) were applied as arcs to the shields of cable samples approximately two feet in length. The samples were then inspected to determine the amount of damage done to the cables either electrically or physically. Some currents were applied to samples both in air and in sand to simulate field conditions. The shield metals included copper, aluminum, stainless steel, low carbon steel and combinations of these metals. These tests were conducted in the continuing program by the Rural Electrification Administration to develop an all-purpose shield for telephone cables. Samples tested in sand with the outer jacket removed exhibited much less core damage than did samples with polyethylene outer jackets.

Introduction

Over the past several years, REA with the cooperation of cable manufacturers, has sought to develop a cable structure in which the metal shield would be (1) capable of providing complete moisture exclusion, (2) acceptable from a corrosion standpoint in direct contact with the earth, and (3) adequate from the standpoint of electrical conductivity for protection purposes. The studies by REA have been primarily concerned with buried type cables. This paper is concerned with the effects of lightning arcs to the shields of buried cables from nearby stroke points. The purpose of these studies was to determine what metal(s) or combination of metals provide the best resistance to electrical and/or physical damage to the cables, especially damage to the cable conductors.

Background

Until recently, REA has advocated the use of copper or copper-clad metals for the shielding of underground and direct burial telephone cables. These metals are highly desirable from standpoints of corrosion and conductivity. The conductivity of 5-mil copper approximates that of 8-mil aluminum used in aerial cables, and both are acceptable from this standpoint. To date, the bare aluminum shield has been unacceptable for use underground because of corrosion considerations. REA, in conjunction with the National Bureau of Standards is currently conducting corrosion tests on a number of metals as possible alternate cable shields to the bare aluminum. It now appears, based on the most recent test data, that a coated aluminum shield is satisfactory for underground and direct burial use where soil resistivities are sufficiently high, that is, 2500 ohm-cm and greater.

A 10-mil copper shield has been specified by REA in areas of the country where gopher attack is probable. Several years ago an additional gopher-resistant shield was introduced in the REA cable specifications. This shield utilizes 2 mils of stainless steel bonded to 4 mils of copper. The copper is evenly divided, with 2 mils on each side of the steel. This has proven to be a satisfactory shield from all aspects. This shield competes economically with the 10-mil copper and shows a 6-mil saving of the red metal. However, REA has been working to eliminate the copper completely, because of its unstable price and supply. A shield has been evaluated for gopher protection which consists of 3 mils of Type 304 stainless steel bonded to 6 mils of aluminum. The stainless steel provides the gopher and corrosion protection with the aluminum providing the conductivity.

An earlier study was made on the effects of lightning surge currents carried by shields of telephone cables[1]. In that study, surge currents were applied directly (without an arc) to the metallic shield of long lengths of cable and the difference in voltage between conductors and shield was measured. It was concluded that some advantage was gained by using magnetic materials. These tests along with corrosion tests are steps in the continuing effort by REA to arrive at an optimum cable shield design at a low cost.

Test Procedure

These tests were conducted on samples of buried cables approximately two feet in length. A typical buried cable construction is shown in Figure 1. A lightning arc was made to occur between an electrode external to the cable, and

*Deceased as of June 7, 1971

1 "Lightning Shielding of Plastic Telephone Cable" by Fisher, Bishop and Robinson of REA 1968 International Wire and Cable Symposium, Atlantic City, New Jersey, December 5, 1968.

the cable shield. Some of the tests were conducted in air and some in a sand box improvised to simulate field conditions. All of the cable conductors were connected together at one end and bonded to the shield(s) and ground. In cable samples having an outer jacket, a current surge was arced to the shield from an external electrode through a small hole made in the outer jacket approximately 1-1/2 feet from the grounded end of the samples. The breakdown was then accomplished at a relatively low voltage (7.7 kV to 18 kV) by placing the electrode against the jacket perforation when the samples were tested in air. In this instance, the small hole in the jacket was filled with metal filings. When tested in the sand box, the sand in the area of the imperfection was saturated with water. Surge current arcs ranging from 18 kA to 83 kA were applied to the samples using a 170 µF generator. (Lightning surge currents to earth average 30 kA.) The test circuit is shown in Figures 2A and 2B. Figure 3 is a typical current wave. A cathode ray oscilloscope (CRO) was used to obtain data for calibration curves between applied potential and current, for the different series controlling resistances. These curves were then used to determine voltages needed to produce various surge currents, using a number of current controlling resistors.

In addition to the tests performed on jacketed samples, tests were also conducted on samples from which the outer jacket had been removed. In these tests the discharge electrode was placed approximately 4 inches from the sample in wet sand and a weight was placed on the sand to simulate compacted soil. The test circuit was then discharged through the sand to the bare shield. All other test conditions were identical to the conditions for the jacketed cables.

The cable samples tested were as follows, with the letter designations in the order that the elements of the cables appear reading out from the core.

Cable Designation	Shield Construction
AP	Aluminum, 8-mil
PAP	Aluminum, 8-mil bonded to outer jacket
PCP	Copper, 5-mil
APFSP	Aluminum, 8-mil; tern plated low carbon steel, 6-mil, flooded with polyethylene grease.
PCSSCP	Copper-clad (430) stainless steel, 6-mil (2+2+2)

In addition to the above, cables incorporating a shield using 3-mil Type 304 stainless steel and 6-mil aluminum (previously mentioned as gopher-resistant) were tested. The size, gauge and core construction were not comparable to any of the above cables. This shield had been corrugated and placed over a standard buried cable and a third jacket placed over the outer shield. Tests on this sample were intended only to see what damage, if any, occurred to the shield material itself.

Tables 1 through 3 list the surge currents for each sample tested, the test medium, and the inner jacket and conductor damage noted.

Results

After testing, the samples were inspected for physical damage to the outer jacket and for deformation of the sample as a whole. The outer jacket was then removed and the shield damage determined. The last step was to inspect the inner jacket, where applicable, and conductors to determine the amount of damage to the core at various applied surge currents.

The outer jackets of the sample cables exhibited a range of damage varying from a slight enlargement of the original imperfection to a blowout of the jacket and shield (Photograph No. 1). The shield damage varied from an evaporation of the outer copper layer on the PCSSCP shield to a complete electrical discontinuity in one of the PAP cables. All of the copper and aluminum shielded cables had holes burned in the metal at all surge currents. Photograph No. 2 illustrates this type of damage. This was not true of the shields containing steel or stainless steel (Photograph No. 3). Only at the higher currents (70 kA and above) were any of these shields burned through.

As a matter of interest, the cable samples with the stainless steel-aluminum laminate were inspected to determine core damage. Although this construction effectively contained two inner jackets, the conductors were damaged in the same manner as the other samples. This evidence along with Tables 1 through 3 indicate that discharge of lightning surge currents through the outer jacket can cause substantial damage to the conductors in the core of the cable.

Table 1 shows that, as might be expected, conductor and shield damage is roughly proportional to the amount of surge current. These tests did not disclose consistent differences in conductor damage for the various shield materials with comparable arcing currents.

Table 2 again shows that damage is proportional to current. A comparison indicates that within the range of materials and dimensions tested, none of these structures was significantly effective in preventing conductor damage.

Damage to the conductors in cables tested with the outer jacket removed (Table 3) was 68 to 96 percent less than when the arc took place through the jacket. Also when the arcing is distributed over a wider section of shield (as in these tests) a beneficial effect in the use of the APFSP shield is indicated.

The sample with the stainless steel-aluminum laminate, tested with the outer jacket removed showed approximately one-third the damage compared to identical samples tested with the jacket in place.

Conclusions

It is concluded that standard present day cables exhibit extensive damage including numerous conductor shiners when subjected to high surge arcing currents through the outer jacket. Core damage as severe as that observed would put most of the cable out of service. It has been shown in the past that cables with a high incidence of shiners develop trouble rapidly due to the presence of central office battery combined with the ingress of moisture. It appears, based on the limited testing done on the jacketless samples, that a cable with a metallic shield directly in contact with the earth has an appreciable advantage over a polyethylene jacketed cable with respect to conductor damage. REA is interested in a cable design such as this; i.e., a corrosion-resistant composite shield sealed to provide an envelope impervious to moisture and having electrical conductivity equivalent to the present 5-mil copper shield.

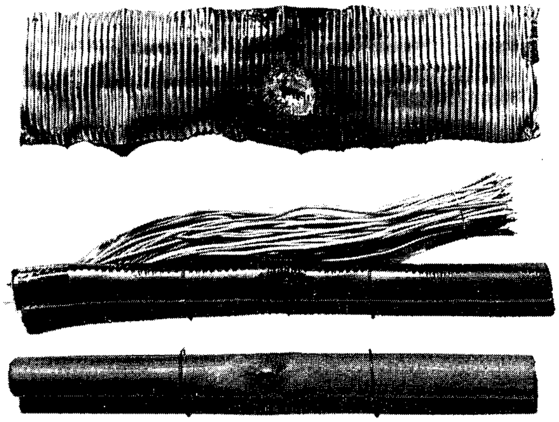
Edwin C. Kelch has been appointed Chief, Outside Plant Branch, Telephone Operations and Standards Division. He succeeds Gerald A. Lohsl who resigned recently to accept a position with private industry.

In his new assignment, Mr. Kelch will direct the activities of an engineering staff in the development of practices, standards and technical data relating to outside plant facilities, equipment and materials.

He has been a member of the REA staff since 1949, first serving as standards engineer in the electric program. He transferred to the telephone program in July 1953 and has since served as standards engineer and Chairman of Technical Standards Committee "A" (Telephone).

Mr. Kelch received a Sustained Superior Performance Award from REA in 1961. He holds a Bachelor of Science Degree in Electrical Engineering from Union College, Schenectady, New York.

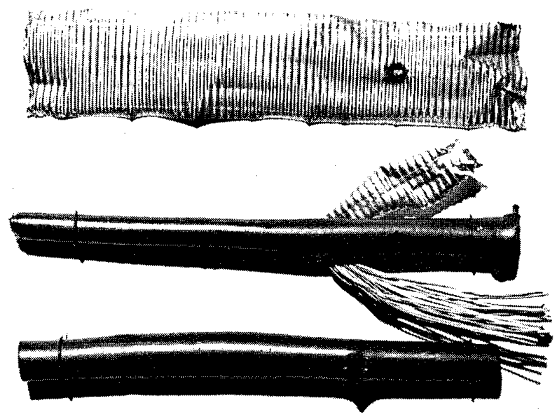
Mr. and Mrs. Kelch and their 4 children make their home in Rockville, Maryland.



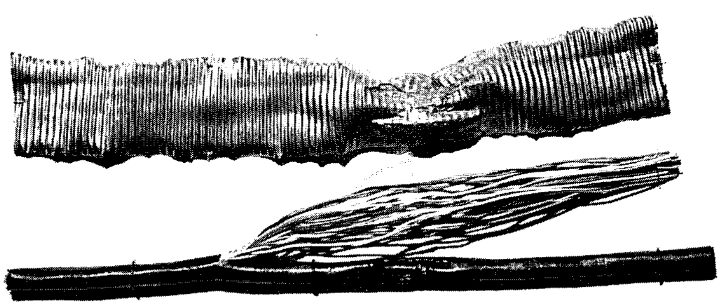
◀ *Sample of PCSSCP cable (bimetallic shield) tested in sand at 50 kA.*

PHOTOGRAPH NO. 1

Sample of APFSP cable (comb. alum. and steel shields) tested in air at 50 kA. ▶



PHOTOGRAPH NO. 2



◀ *Sample of PCSSCP cable (bimetallic shield) tested in sand at 60 kA.*

PHOTOGRAPH NO. 3

TABLE 1

JACKETED CABLE SAMPLES TESTED IN AIR

TYPE OF CABLE	AMOUNT OF SURGE CURRENT	DAMAGE NOTED: INNER JACKET	DAMAGE NOTED: NUMBER OF CONDUCTOR SHINERS
12 pr., 24 gauge AP	18.3	-	1
" " "	30.0	-	1
" " "	50.0	-	3
" " "	70.0	-	3
12 pr., 24 gauge PAP	30.0	Indented	2
" " "	50.0	1 Pinhole	2
" " "	70.0	3 Pinholes	4
12 pr., 24 gauge PCP	40.0	Surface Deformed	0
" " "	83.0	1 Pinhole	5
12 pr., 24 gauge APFSP	50.0	Indented	1
" " "	70.0	Indented	6
" " "	83.0	Indented	9

TABLE 2

JACKETED CABLE SAMPLES TESTED IN SAND

TYPE OF CABLE	AMOUNT OF SURGE CURRENT	DAMAGE NOTED: INNER JACKET	DAMAGE NOTED: NUMBER OF CONDUCTOR SHINERS
12 pr., 24 gauge AP	30.0		5
12 pr., 24 gauge PAP	30.0	Indented	0
" " "	50.0	One ¼" Hole	11
" " "	70.0	Two ¼" Holes	16
12 pr., 24 gauge PCP	40.0	Surface Deformation	11
" " "	70.0	1 Pinhole	17
" " "	83.0	1 Pinhole	11
25 pr., 22 gauge PCP	30.0	Indented	11
" " "	50.0	Indented	12
12 pr., 24 gauge PCSSCP	18.3	Indented	4
" " "	27.5	Indented	12
" " "	29.5	Indented	6
" " "	40.0	Indented	16
" " "	50.0	Indented	15
" " "	60.0	¼" x 1/16" Hole	19
25 pr., 24 gauge PCSSCP	30.0	Indented	9
" " "	50.0	Indented	25
12 pr., 24 gauge APFSP	70.0	Indented	17
" " "	78.0	Indented	13

TABLE 3

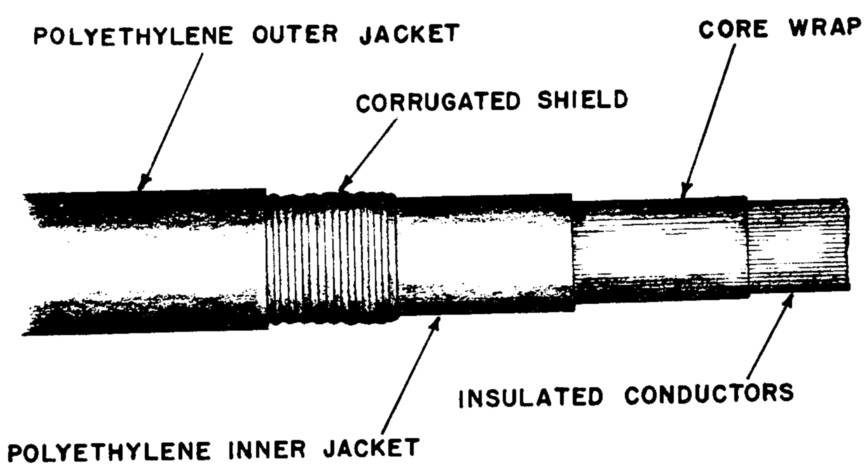
UNJACKETED CABLE SAMPLES TESTED IN SAND

TYPE OF CABLE	SURGE CURRENT	DAMAGE NOTED: INNER JACKET	DAMAGE NOTED: NUMBER OF CONDUCTOR SHINERS
12 pr., 24 gauge PCP	70.0	Surface Deformation	2
25 pr., 22 gauge PCP	50.0	Surface Crazing	3
12 pr., 24 gauge PCSSCP*	60.0	Indented	6
25 pr., 22 gauge PCSSCP*	50.0	Indented	1
12 pr., 24 gauge APFSP**	70.0	Indented	0

*Single shield - copper-clad stainless steel
**Two shields - (1) aluminum
(2) flooded steel

Fig. I

TYPICAL DIRECT BURIAL CABLE



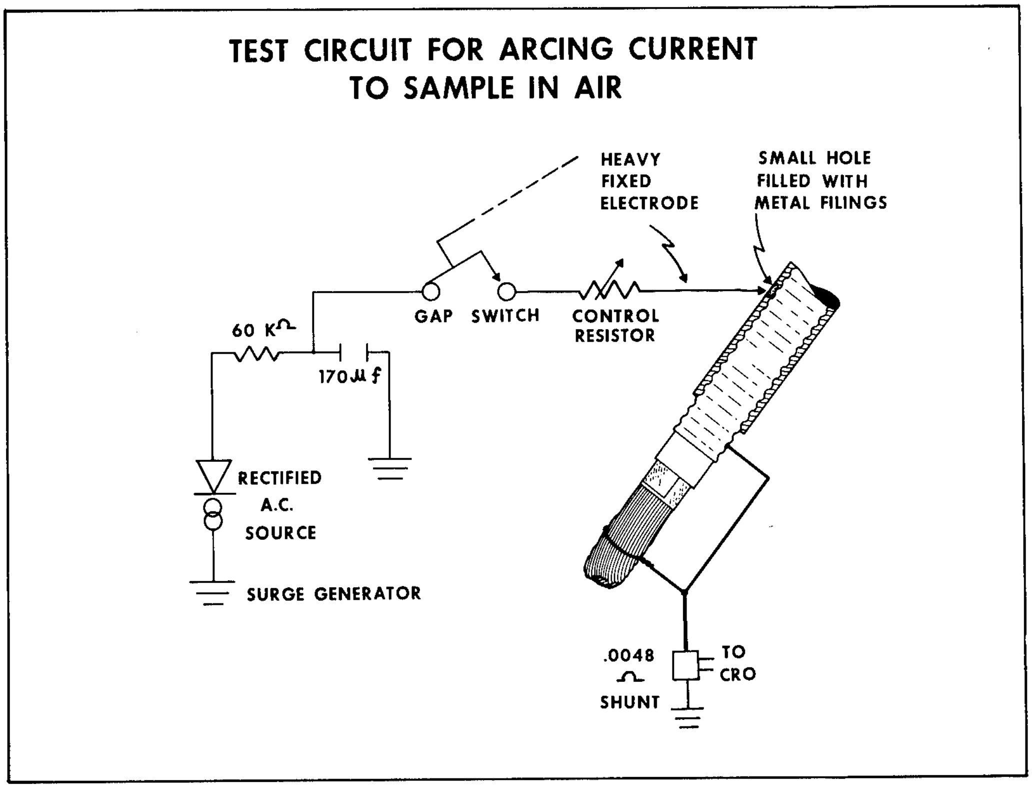

TEST CIRCUIT FOR ARCING CURRENT
TO SAMPLE IN AIR
HEAVY
FIXED
ELECTRODE
SMALL HOLE
FILLED WITH
METAL FILINGS
GAP SWITCH
CONTROL
RESISTOR
60 KΩ
170 µf
RECTIFIED
A.C.
SOURCE
SURGE GENERATOR
.0048
Ω
SHUNT
TO
CRO

Fig.2A

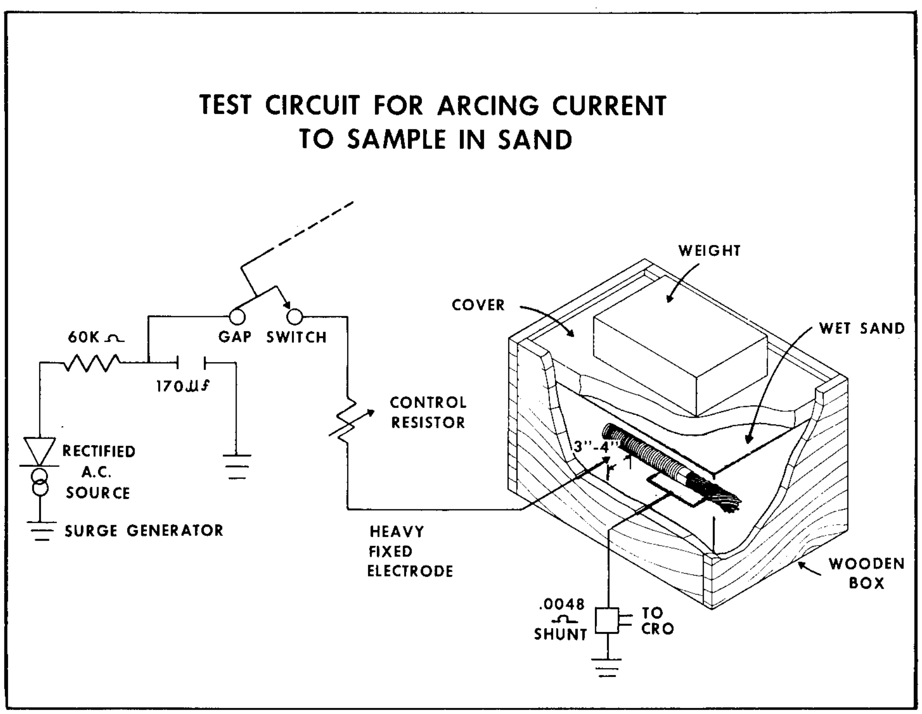

TEST CIRCUIT FOR ARCING CURRENT
TO SAMPLE IN SAND
WEIGHT
COVER
WET SAND
60K Ω
GAP SWITCH
170µf
CONTROL
RESISTOR
RECTIFIED
A.C.
SOURCE
SURGE GENERATOR
3''-4''
HEAVY
FIXED
ELECTRODE
WOODEN
BOX
.0048
Ω
SHUNT
TO
CRO

Fig.2B

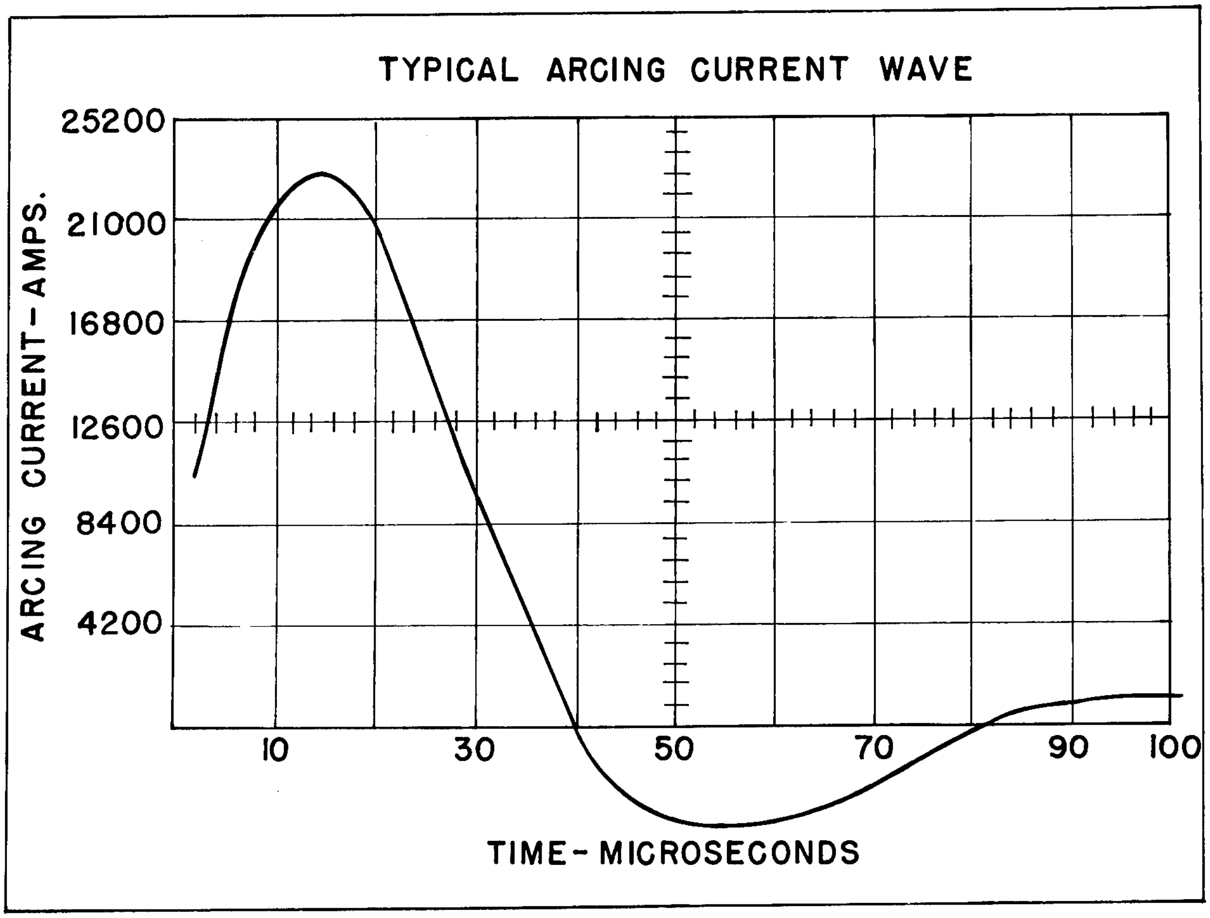

TYPICAL ARCING CURRENT WAVE
25200
21000
16800
12600
8400
4200
ARCING CURRENT - AMPS.
10
30
50
70
90
100
TIME - MICROSECONDS

Fig. 3

LIGHTNING INDUCED CURRENT SURGES ON A BURIED MULTICOAXIAL CABLE SYSTEM

by

D. A. Douglass
Bell Laboratories
Murray Hill, New Jersey

Abstract

Lightning flashes to the shield of a buried multicoaxial cable induce current surges on the enclosed coaxial conductors. A distributed source transmission line model quantitatively relates these current surges to the lightning current. Published statistical data on lightning currents is then used to predict the magnitude and frequency of the induced current surges on coaxial conductors.

Introduction

The latest broadband coaxial transmission system proposed by the Bell System is called the L-5 Carrier System. When fully loaded, it provides 90,000 two-way message channels. A field trial is presently underway and initial service is planned for 1973. Because of its extremely high capacity, the reliability requirements are severe. This paper deals with the problem of predicting the magnitude and frequency of occurrence of lightning-induced current surges that the L-5 equipment must survive.

The bulk* of the proposed L-5 carrier system will be made up of buried "CLOAX"[1] (corrugated, laminated coaxials) multicoaxial cable terminated at 75-mile intervals by dc power converters, with repeaters spaced approximately every mile in between. The CLOAX cable contains twenty-two 0.375 inch dia. coaxial tubes arranged in an inner layer of eight and a surrounding layer of fourteen (see Figure 1). The coaxials consist of an inner conductor of copper wire held in the center of an outer coaxial by plastic disks

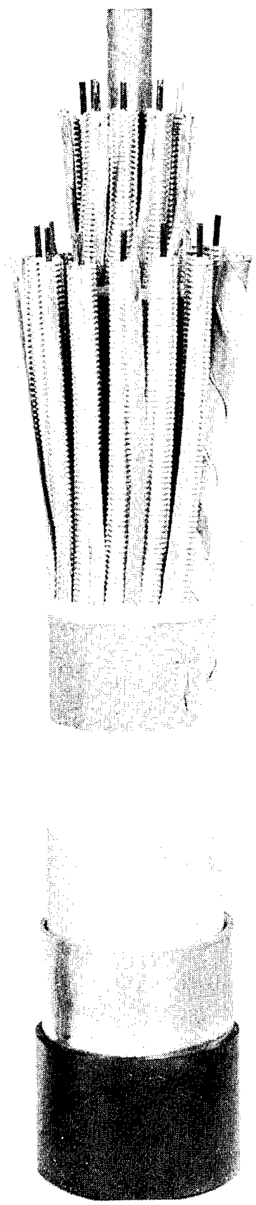


Figure 1. CLOAX multicoaxial cable. The cable pictured here has only 12 tubes in the outer layer. The more recent version considered in the text is identical except for the addition of two tubes in place of interstitial pairs in the outer layer.

*Some sections will be shorter than 75 miles.

spaced one inch apart. The outer coaxial conductor is a new corrugated copper-steel laminate. The outer ring of coaxial conductors is surrounded by a layer of paper, a 75-mil layer of polyethylene, another layer of paper, a 110-mil layer of lead, and a 75-mil outer jacket of black polyethylene.

At each repeater manhole (1-mile spacing), and at the power converters (75-mile spacing), all of the coaxial outer conductors are bonded to the lead shield and to local ground. The power-input voltage to the repeaters is regulated by the voltage across a reverse biased 18-volt avalanche diode, in series with each center conductor at every repeater manhole.* Because the diode does not develop high voltages at high currents, it is not possible to use parallel, voltage-operated protection for the diode. Placing a fuse or current-limiting device in series with the diode is equally unacceptable because of the high reliability requirements of the L-5 system. Thus, the diode must be designed to conduct lightning-induced surge currents without damage.

It is the purpose of this paper to predict the magnitude and frequency of lightning induced currents on the coaxial center conductors of the L-5 system. In a more general sense, however, the methods employed here allow lightning protection to become a consideration in the initial design of buried, multicoaxial cable systems. Proposed changes in cable sheath or coaxial conductor design, for instance, may be exaluated in terms of predicted lightning damage rates early in the design process. Thus although we shall consider only the L-5 system, the general method allows lightning protection to become a design consideration rather than a remedial measure after installation.

Coaxial Center Conductor Current as a Function of Lightning Flash Current

This section relates the coaxial center conductor current to a general lightning flash current.

*The dc current flowing in the reverse biased zener diodes is ≈125 mA. In half of the coaxial center conductors this current flows one way, and in the rest, the opposite way.

A 75-mile section of the L-5 system is shown schematically in Figure 2. A direct lightning flash is assumed to have contacted the lead shield at x = 0. The possibility of a short (caused by lightning crushing) between inner and outer coaxial conductors is indicated by the switch also at x = 0.

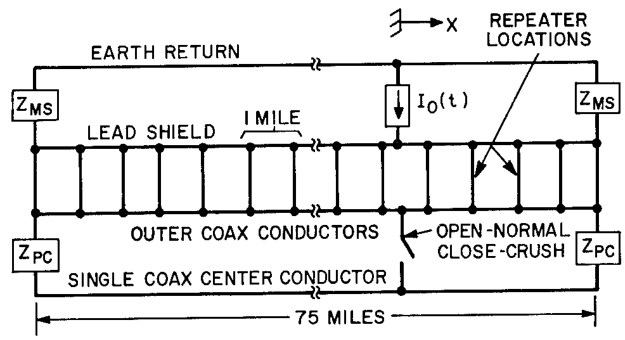


Figure 2. Schematic Diagram of a 75-mile section of the L-5 cable system.

Z_{MS} ≡ main station impedance to remote earth

Z_{PC} ≡ main station power converter impedance from coax center conductor to local station ground

$I_o(t)$ = Lightning Flash Current

The impedance of each manhole to remote earth is assumed much larger than the power converter impedance to remote earth and is neglected. This is a conservative assumption since a finite manhole resistance would result in a lesser induced center-conductor current.

The periodically shorted lead shield-coaxial outer conductor may be modelled as a laminated shield, and transmission line effects within the laminated shield may be neglected for wavelengths >>1 mile. The transmission line model can thus be considerably simplified (as shown in Figure 3) since the frequency spectra of the lightning-induced current and voltage in this laminated shield consists primarily of frequencies below 20 KHz (wavelengths ≥ 3 miles).

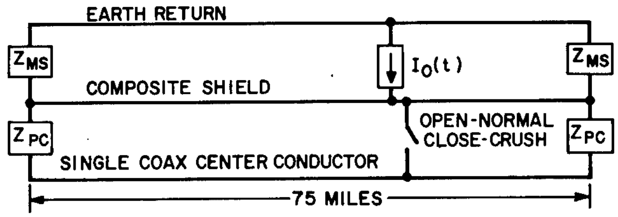


Figure 3. Simplified coupled transmission line model of a 75-mile section of the L-5 cable system.

Considering the simplified coupled transmission lines of Figure 3, suitable equations may be derived in a straightforward manner (see Appendix I). The equations relating the center conductor current and the shield-earth (with an assumed exponential time variation) are:

$$\frac{d^2 i_o(\omega,x)}{dx^2} = i_o(\omega,x)\,\Gamma_o^2(\omega) - Z_T(\omega)Y_o(\omega)i_{SH}(\omega,x) \qquad \text{(A)}$$

$$\frac{d^2 i_{SH}(\omega,x)}{dx^2} = i_{SH}(\omega,x)\,\gamma_{SH}^2(\omega) - Z_T(\omega)Y_{SH}(\omega)i_o(\omega,x) \qquad \text{(B)}$$

$\omega \equiv$ angular frequency in radians

$i_o(x) \equiv$ coax center conductor current [amperes]

$i_{SH}(x) \equiv$ current in shield-earth circuit [amperes]

$\Gamma_o \equiv$ propagation constant of 0.375" coax transmission circuit [meter^{-1}]

$Y_o \equiv$ admittance per meter of 0.375" coax transmission circuit [mhos/meter]

$\gamma_{SH} \equiv$ propagation constant of shield-earth transmission circuit [meter^{-1}]

$Y_{SH} \equiv$ admittance per meter of shield-earth transmission circuit [mhos/meter]

$Z_T \equiv$ transfer impedance of laminated shield. [ohms/meter]

Generally, $|i_o(x)| << |i_{SH}(x)|$ and $Z_T(\omega)Y_{SH}(\omega) \leq \gamma_{SH}^2(\omega)$, so the second term on the right side of Equation (B) is negligible.

The transfer impedance of the laminated shield (Z_T) is measured as shown in Figure 4. Note that the measurement was made on a 150-foot length of CLOAX cable (Z_T is specified in ohms per unit length) and that the magnitude of Z_T is down two orders of magnitude from its dc value at 25 kHz. Thus, any resonance phenomena in the laminated shield at these higher frequencies will not significantly alter our predictions of lightning-induced currents made neglecting such resonances.

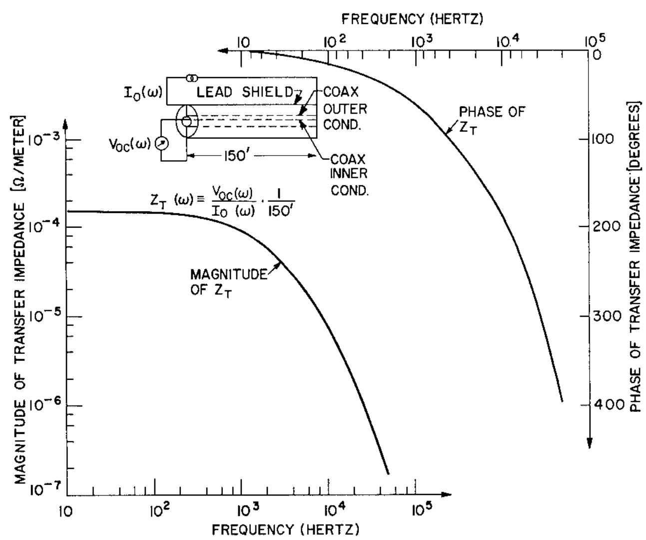


Figure 4. Experimental arrangement and resultant estimate of transfer impedance measurement for CLOAX cable. Z_T shown is for a tube in the outer layer. $|Z_T|$ for a tube in the inner layer is less than that plotted at all frequencies.

The boundary conditions applied to the 75-mile coupled transmission line are as follows. The coax center conductor-composite shield line is terminated in the power converter input impedance* (see Figure 5). The composite shield-earth

*This assumes that the coax dielectric strength is sufficient to prevent shorts between the stroke point and the converter.

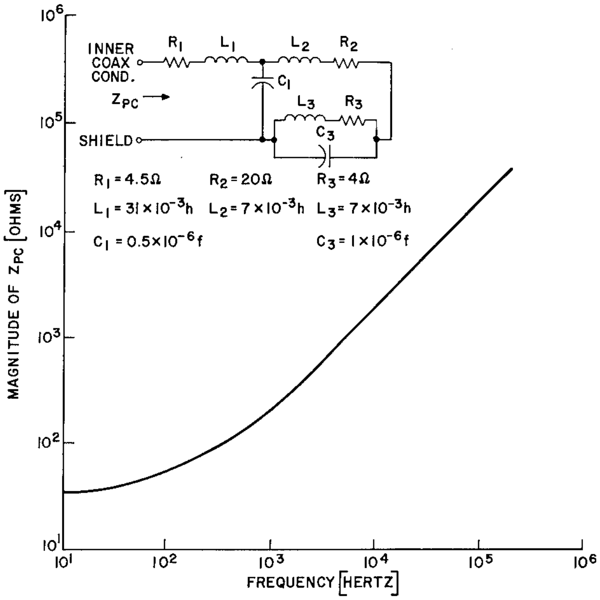


Figure 5. Low frequency equivalent circuit for main station power converter and separation filter impedance.

line is terminated at each main station by the main station impedance to ground (Z_{MS}) which is assumed to be 10Ω.

In order to calculate the surge current in the coax center conductor, we must recognize two distinct situations in which a lightning flash to the cable shield can induce current through the diodes:

Case 1 — There is a lightning flash to the cable shield at a point between the main stations, but the cable is not damaged.

Case 2 — There is a lightning flash to the cable shield at a point between the main stations and the coaxial tube under consideration is shorted at that point.

In Figure 3, the switch normally open (for Case 1) may be closed for Case 2. In Appendix I, solutions for diode current are found for Cases 1 and 2.

For both Case 1 and Case 2, the center conductor current is found to depend on the lightning flash current waveshape, the distance of the flash point from a main station, and the distance of the measuring point from the flash point, and on the cable parameters and terminations.

For Case 2 (inner and outer coaxial conductors shorted), we have assumed that only one tube is shorted and that this tube is shorted for the whole duration of the lightning flash current. By eliminating the nonlinear switch of Figure 2, we enormously simplify calculations with the result that our estimate of center conductor current is again somewhat high. To assume that only one tube is shorted is also conservative, since if more than one tube were shorted, the center conductor current would be lessened by the increased parallel conductivity of the other center conductors.

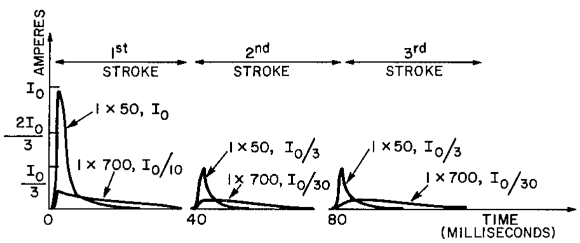
The particular cable parameters used in calculations of coaxial center conductor surge current are described in Appendix II.

We have related the coax center conductor current to a general lightning flash current. In the next section, we shall specify the lightning current.

Lightning Flash Current

The current due to a lightning flash to earth (and including those which arc to the L-5 cable) may consist of some one to twenty-six separate current peaks corresponding to repeated ionizations of the same flash channel. Each of these current peaks (referred to hereafter as "strokes") is followed by a somewhat smaller magnitude, slower decaying current called an "intermediate current." During the time between repeated strokes a much lower magnitude "continuing current" is sometimes observed. This whole series of current pulses is called a "flash." A typical current associated with a lightning flash to ground is pictured and described mathematically in Figure 6. This description is inspired by Section 4.3 of M. A. Uman's book, "Lightning."[2] Note that continuing current is neglected since reliable statistical data is lacking.

The number of strokes (3), the decay time to half-peak current of each stroke (50μsec), and the rise time of the strokes (1μ sec) are average



$$I(t) = \left[I_0\left(e^{-at} - e^{-bt}\right) + \frac{I_0}{10}\left(e^{-ct} - e^{-dt}\right)\right] U(t)$$

$$+ \left[\frac{I_0}{3}\left(e^{-a(t-\tau)} - e^{-b(t-\tau)}\right) + \frac{I_0}{30}\left(e^{-c(t-\tau)} - e^{-d(t-\tau)}\right)\right] U(t-\tau)$$

$$+ \left[\frac{I_0}{3}\left(e^{-a(t-2\tau)} - e^{-b(t-2\tau)}\right) + \frac{I_0}{30}\left(e^{-c(t-2\tau)} - e^{-d(t-2\tau)}\right)\right] U(t-2\tau)$$

WHERE $U(t) = \begin{pmatrix} 0 \text{ FOR } t < 0 \\ 1 \text{ FOR } t \geq 0 \end{pmatrix}$

$\tau = 40$ MILLISECONDS (ASSUMED CONSTANT FOR FLASH)

$a = 16 \times 10^3 \text{ sec}^{-1}$

$b = 5 \times 10^6 \text{ sec}^{-1}$

$c = 1 \times 10^3 \text{ sec}^{-1}$

$d = 5 \times 10^6 \text{ sec}^{-1}$

Figure 6. Typical multiple stroke current associated with a single lightning flash to ground.

values, as is the ratio of successive peak stroke currents. I_0, the peak stroke current of the first (and largest) stroke, is a random variable. This estimate for I(t) is used in all calculations performed in this paper.

It should also be noted that the lightning flash current is modeled here as a current source between shield and earth, independent of the cable or earth resistivity. This assumption has been repeatedly justified in previous studies because of the high internal impedance of the stroke channel to ground.[3]

The lightning currents that the L-5 cable will be exposed to must be estimated on a statistical basis. The literature concerning the statistics of lightning currents typically considers only one variable at a time (i.e., peak current, rate of rise of a single stroke, or time between subsequent strokes in a flash). The most complete statistical data describes the peak stroke current I_0 (of all strokes in a flash) for flashes to aerial structures. This statistical distribution has been modified by E. D. Sunde[3] (as shown in Figure 7) for strokes to buried cables (small flashes do not arc to buried conductors). The other variables of flash current have been given reasonable mean values; the lightning flash current, I(t), has been related to the peak stroke current, I_0. The statistical variation of I_0 is estimated from Figure 7; thus, the statistical variation of I(t) may be derived from Figure 7.

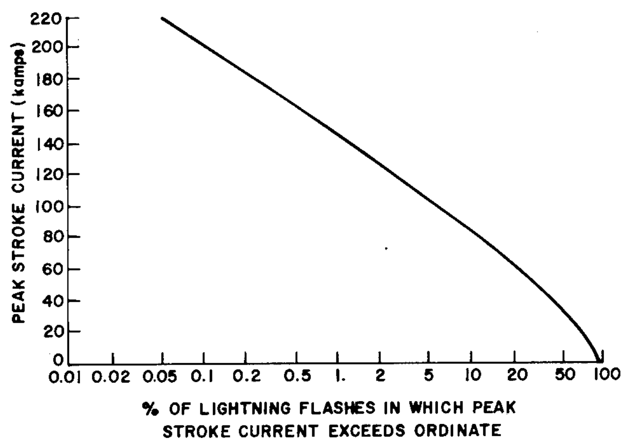


Figure 7. Distribution of peak initial stroke currents (I_0) for lightning flashes to buried cables.

Frequency of Occurrence of Lightning Flashes to Buried L-5 Cable

It is the purpose of this section to find the number of lightning flashes which arc to a 75-mile cable section each year neglecting the presence of shield wires.* This calculation is performed so as to allow a final estimate of the number of times per year that an L-5 "power pickoff" diode will pass a certain level of charge (Q) or peak current (I_{peak}) due to lightning flashes to the 75-mile L-5 cable section.

*Shield wires placed approximately 2 feet above the cable during installation may prevent small magnitude lightning flashes from arcing to the cable and reduce the lightning current entering the cable shield for larger flashes. Ignoring their presence is thus somewhat conservative.

The probability of flashes to the cable sheath is assumed uniform between main stations. Thus the lightning flash is equally likely to occur at any point along the cable's length. This assumption was verified by Dr. G. T. Hawley.[4]

The following argument closely parallels that in the H. M. Trueblood and E. D. Sunde paper, "Lightning Current Observations in Buried Cable."[5]

The number of lightning flashes arcing to the buried L-5, 75-mile (1.21×10^5 meters), cable section may be expressed as:

$$N = 2 \times 1.21 \times 10^5 \times \bar{r} \times n$$

where

$\bar{r}$ ≡ effective arcing distance (in meters) over which a flash to earth will arc to the cable

$$\cong 0.3 \times \rho_{soil}^{1/2} \quad \left\{ \begin{array}{l} \rho_{soil} \text{ is the soil resis-} \\ \text{tivity in meter-ohms.} \end{array} \right\}$$

and

n ≡ number of flashes to earth per square meter per year in the region of interest

$$\simeq TD \times 9.3 \times 10^{-8} \quad \left\{ \begin{array}{l} \text{TD is the annual} \\ \text{number of thunder-} \\ \text{storm days in the} \\ \text{region of interest.*} \end{array} \right\}$$

By overlaying maps of earth resistivity[6] and thunderstorm activity[7] the product of $\rho_{soil}^{1/2}$ and TD is found to be less than 1100 in 95 percent of the United States land areas, so that a reasonable worst case estimate is:

$$N_{95\%} \simeq 2 \times 1.21 \times 10^5 \times 0.3 \times 1100 \times 9.3 \times 10^{-8}$$

$\simeq$ 7.4 lightning flashes to the shield of a 75-mile section of buried cable per year.

Probability of Shorts (Case 2)

Experience, field studies, and various calculations lead to the conclusion that lightning seldom, if ever, induces sufficient voltage between inner and outer coaxial conductors to cause arcing. The dielectric strength of physically intact pressurized coaxials is of the order of 3000 Vdc. Worst case estimates of lightning-induced voltages are less than 1000 volts peak.

Field experience does indicate that approximately 1 percent of lightning strokes to large buried multicoaxial cables result in denting[8] (mechanical shorting) of an average of half of the cable's coaxials. Thus, the only means of causing a coaxial short is assumed to be denting due to direct lightning flashes to the buried cable shield. This occurs for 1 percent of the flashes to the cable, and for any particular coaxial the probability of shorting given a lightning flash to the cable is 5×10^{-3}.

Frequency of Occurrence of Center Conductor Current Surges

Numerical calculations of lightning-induced surge currents on the coaxial center conductors indicate that the magnitude and duration are generally a weak function of position (X) between the main station (X = 0) and the point where the lightning flash arcs to the cable shield ($X = X_0$). This surge current does depend quite strongly on the distance from flash point to main station (X_0). In the following, the variation of Q and I_{peak} with position (X) is eliminated by using the maximum calculated value for each distance, X_0. Figures 8 and 9 indicate the resultant maximum values of Q and I_{peak} for each distance, X_0.

In order to remove the variable, X_0, from functions Q and I_{peak}, the mean value of Q and I_{peak} may be calculated over all X_0 from 0 to 120 Km, assuming (as noted previously) that the occurrence of a stroke between main stations is equally probable at each point. The mean values are calculated by a conservative numerical integration of the curves of Figures 8 and 9. This information allows calculation of Q and I_{peak} independent of the distance of the lightning flash from the main stations. Thus:

$$Q_{no\ crush}[\text{coul.}] = 5.3 \times 10^{-5} \times I_0[\text{kiloamperes}]$$

*I have assumed that there are 0.24 lightning flashes to earth per square mile per thunderstorm day.

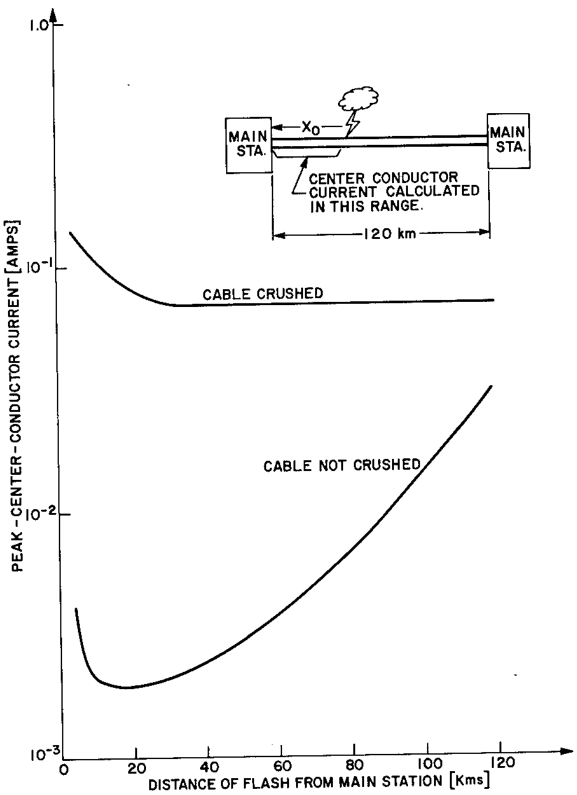


Figure 8. Magnitude of coax center conductor current as a function of X_0, for a peak stroke current of 1000 amperes. The maximum Q calculated for each X_o is plotted.

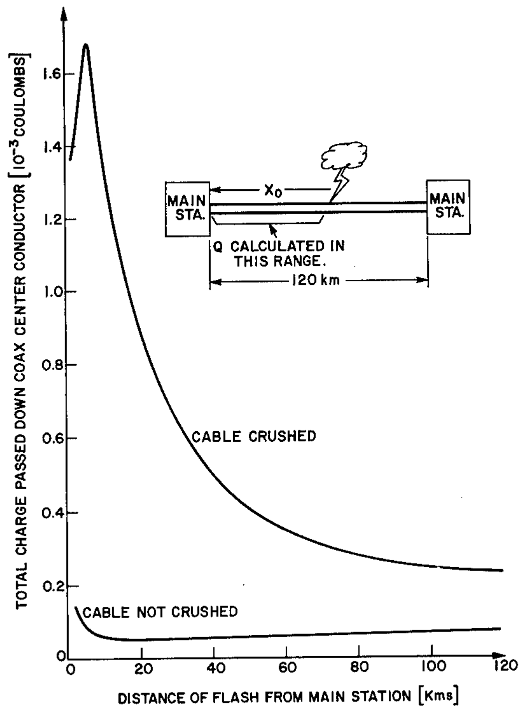


Figure 9. Total charge passing through center conductor as a function of X_0, the distance from flash to main station. The first stroke peak current is 1000 amperes. The maximum Q calculated for each X_0 is plotted.

$$I_{peak/no\ crush}[\text{amps}] = 7.3\times10^{-3}\times I_o[\text{kiloamperes}]$$

$$Q_{crush}[\text{coul.}] = 5.3\times10^{-4}\times I_o[\text{kiloamperes}]$$

$$I_{peak/crush}[\text{amps}] = 8.1\times10^{-2}\times I_o[\text{kiloamperes}]$$

Using the statistical data given in Figure 7 on peak stroke currents, I_o, it is possible to calculate from the above equations the percentage of lightning flashes to the 75-mile L-5 cable section which exceed any given value of Q or I_{peak} from the above equations. This percentage of flashes which exceed Q or I_{peak} is decreased by one-half because only current in the diode's reverse conduction direction can cause damage. Thus the statistical estimates of Q and I_{peak} given in Figures 10 and 11 account for the fact that only diodes to one side of the flash point will be damaged.

$P_{I_{peak}\ (or\ Q)/crush\ (or\ no\ crush)}$ is defined as the probability of exceeding I_{peak} (or Q), given that the cable is crushed (or not crushed) by a lightning flash to the cable shield.

The estimates of $P_{I_{peak}/crush}$, $P_{I_{peak}/no\ crush}$, $P_{Q/crush}$ and $P_{Q/no\ crush}$ given in Figures 10 and 11 can be combined with the previously determined values for the probability of crushing or not crushing the cable, in order to find P_Q and $P_{I_{peak}}$. Previously, for any coaxial tube in the cable we found that

$$P_{crush/flash} \cong 0.005$$

$$P_{no\ crush/flash} \cong 0.995$$

Now $P_{Q/flash}$ and $P_{I_{peak}/flash}$ may be calculated:

$$P_{I_{peak}/flash} = P_{I_{peak}/crush}\times P_{crush/flash} + P_{I_{peak}/no\ crush}\times P_{no\ crush/flash}$$

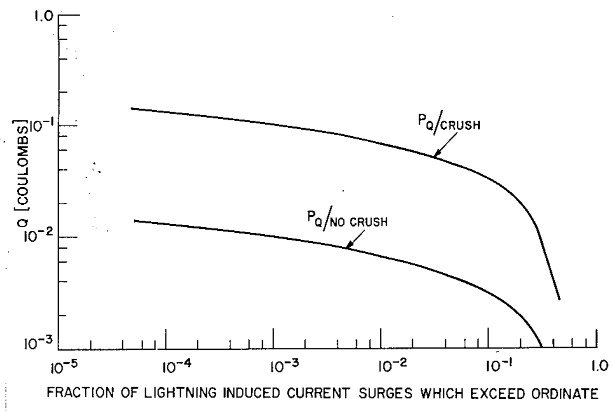


Figure 10. Fraction of lightning flashes to 75-mile L-5 cable section which induce a Q which exceeds the ordinate value in diode's reverse direction for case numbers 1 and 2.

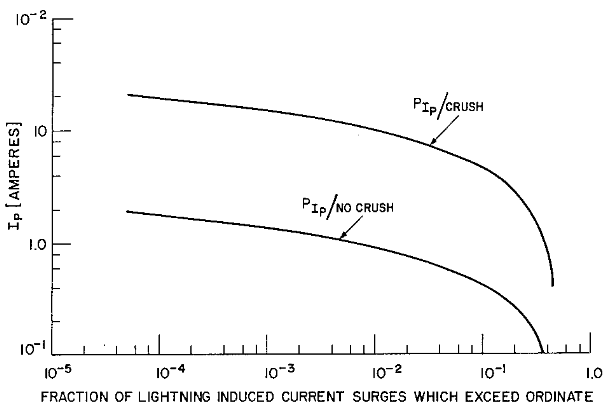


Figure 11. Fraction of lightning flashes to 75-mile L-5 cable section which induce an I_p exceeding the ordinate value in the diode's reverse direction for case numbers 1 and 2.

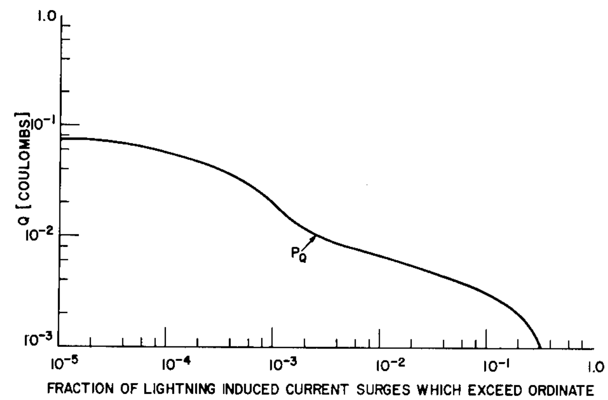


Figure 12. Fraction of lightning flashes to 75-mile section of L-5 cable that induce a Q which exceeds the ordinate in any given diode's reverse direction.

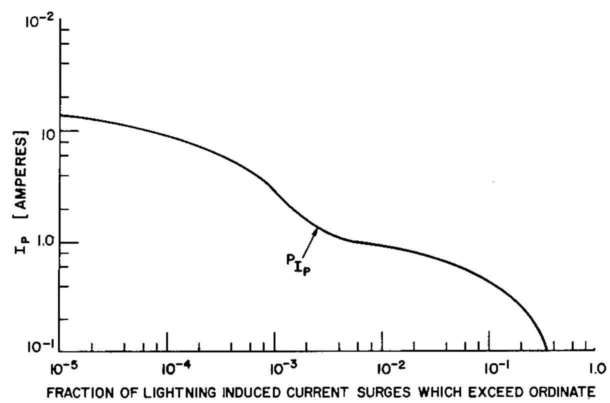


Figure 13. Fraction of lightning flashes to 75-mile section of L-5 cable that induce a Q which exceeds the ordinate in any given diode's reverse direction.

$$P_{Q/\text{flash}} = P_{Q/\text{crush}} \times P_{\text{crush/flash}} + P_{Q/\text{no crush}} \times P_{\text{no crush/flash}}$$

This is done in Figures 12 and 13.

Finally, the frequency of occurrence of center conductor current surges of Q and I_{peak} for a given cable section may be calculated by multiplying $P_{Q/\text{flash}}$ or $P_{I_{peak}/\text{flash}}$ by the number of flashes per year.

$$N_{Q(I_{peak})} = P_{Q(I_{peak})} \cdot N_{\text{flashes}}$$

$N_{Q(I_{peak})}$ ≡ number of times per year that $Q(I_{peak})$ is exceeded

N_{flashes} ≡ number of flashes to cable section per year

Using $N_{\text{flashes}} = 7.4$, which was derived in the last section, N_Q and $N_{I_{peak}}$ are found in Figures 14 and 15.

The application of Figures 14 and 15 must be fully understood.

1. If a single diode fails then it is highly likely that several other diodes in a series with it, between the flash point and main station, will also fail.
2. If a crush occurs, then on the average, half of the cable's coaxial tubes will be crushed. Thus if diodes in one coax string are damaged other strings are likely to be damaged as well.

A "diode failure", then, will probably herald a major disruption of service.

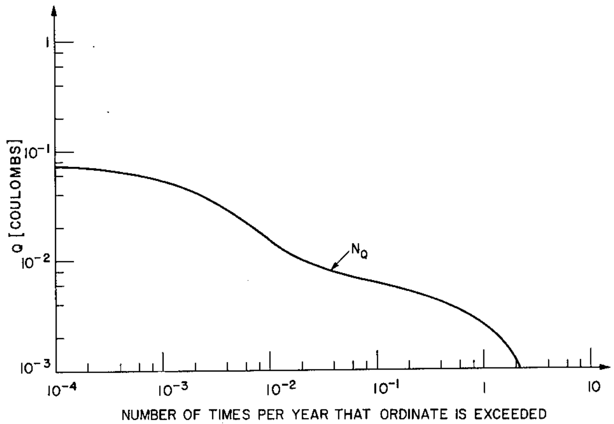


Figure 14. Annual frequency of occurrence of lightning induced charge flow in "power pickoff" diode's reverse conduction direction which exceeds ordinate.

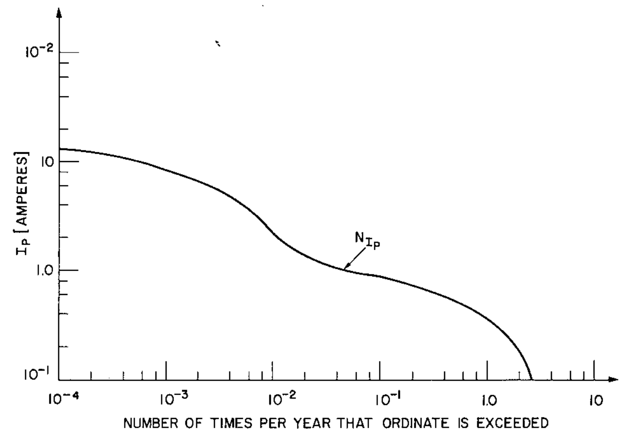


Figure 15. Annual frequency of occurrence of lightning induced peak current in "power pickoff" diode's reverse conduction direction which exceeds ordinate.

Derivation of Test Waveform

The graphs of Figures 14 and 15 may be used to derive a diode current test waveform in the following manner. Simulating the largest diode current surge occurring in 10^4 years, we find a peak current of 13 amperes (from Figure 15), and a Q of 0.074 coulombs (Figure 14). Assuming a test wave of the form

$$I(t) = I_o e^{-\ln 2/\tau_{1/2} t}$$

the time can be found to half peak current, $\tau_{1/2}$, for a Q and I_{peak} as above:

$$Q = \int_0^\infty I_{peak} e^{-\ln 2/\tau_{1/2}} dt$$

$$\frac{Q}{I_{peak}} = \frac{1}{\frac{\ln 2}{\tau_{1/2}}} = \frac{\tau_{1/2}}{\ln 2}$$

$$\tau_{1/2} = \frac{Q}{I_{peak}} \ln 2 = \frac{.074}{13} \ln 2$$

$$= 3.9 \text{ milliseconds}$$

Summary

The L-5 System employs a multicoaxial cable made up of 22 coaxial conductors surrounded by a polyethylene jacket which in turn is surrounded by a polyethylene covered lead shield. Repeaters for each coaxial circuit occur every mile. The repeaters are remotely powered by dc converters placed every 75 miles. The voltage across a reverse biased zener diode in series with each center conductor at each repeater "picks-off" power for the repeater. When lightning flashes arc to the lead shield of this cable, a current surge is induced in the coaxial center conductors that must be carried without damage by these "power pickoff diodes."

Combining a relatively simple coupled transmission line model of lightning flashes to a 75-mile L-5 section with statistical predictions of lightning current, the frequency of occurrence of lightning-induced currents on the cable's coaxial center conductors is estimated.

As a result of this analysis, the lightning protection of the L-5 system has become a part of the initial design of that system. A similar method of analysis may be used to estimate current or voltage surges from lightning on any buried, multicoaxial cable system.

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Appendix I
Solution of Coupled Transmission Line Equations

Assume that modeling the L-5 cable system as two coupled transmission lines is valid. Then I shall derive the surge current induced in a coaxial tube center conductor as a result of a lightning stroke to the L-5 cable shield. The cable-earth coupled transmission line model was illustrated in Figure 2 and is repeated here for convenience as Figure AI-1.

The derivation of the current in the coax center conductor $[i_o(x)]$ is straightforward. Consider an infinitesimal section of coupled transmission line (Figure AI-2) where the coupling factor is the transfer impedance of the composite shield, Z_T. This particular arrangement of the distributed parameters, Z_{SH}, Y_{SH}, Z_O, and Y_O, is for conceptual ease. Note that the transfer impedance, Z_T, couples the two transmission lines.

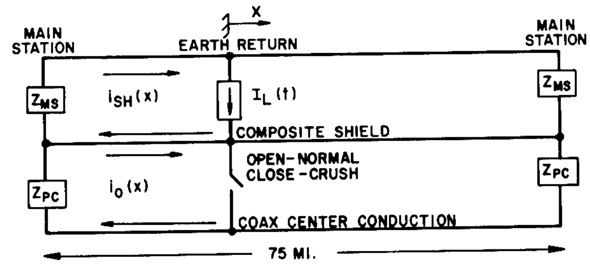

Figure AI-1. Coupled transmission line model for 75-mile section of L-5 cable, indicating terminations of shield-earth and coax center conductor-shield transmission lines.

Z_{MS} = main station impedance to remote earth

Z_{PC} = power converter impedance

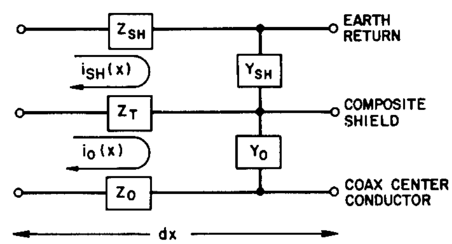

Figure AI-2. A differential element of the above coupled transmission line model of L-5 buried cable.

Writing loop and node equations for the differential element of Figure AI-2 (assuming sinusoidal variations), equations for the currents in the two lines, $i_o(x)$ and $i_{SH}(x)$ are found.

$$\frac{d^2 i_o(x)}{dx^2} = \Gamma_o^2 \cdot i_o(x) - Z_T Y_o \cdot i_{SH}(x) \qquad (1)$$

$$\frac{d^2 i_{SH}(x)}{dx^2} = \gamma_{SH}^2 \cdot i_{SH}(x) - Z_T Y_{SH} \cdot i_o(x) \qquad (2)$$

$i_o(x) \equiv$ coax center conductor current

$i_{SH}(x) \equiv$ earth return current

$\Gamma_o(\omega) \equiv \sqrt{Z_o(\omega) Y_o(\omega)} \equiv$ propagation constant of 0.375" diameter coax

$Y_o(\omega) \equiv$ admittance per meter of 0.375" diameter coax

$\gamma_{SH}(\omega) \equiv \sqrt{Z_{SH}(\omega) Y_{SH}(\omega)} \equiv$ propagation constant of shield earth transmission line

$Y_{SH}(\omega) \equiv$ admittance per meter of shield earth transmission line

$Z_T(\omega) \equiv$ transfer impedance of laminated shield

Generally, $|i_o(x)| << |i_{SH}(x)|$ and $Z_T(\omega) \times Y_{SH}(\omega) \leq \gamma^2_{SH}(\omega)$, so the second term on the right-hand side of Equation (2) may be neglected. If this is done, the solutions for $i_o(x)$ and $i_{SH}(x)$ may be written:*

$$i_{SH}(x) = C_1 e^{-\gamma_{SH} x} + C_2 e^{+\gamma_{SH} x} \tag{3}$$

$$i_o(x) = [A + P(x)]\, e^{-\Gamma_o x} - [B + Q(x)]\, e^{+\Gamma_o x} \tag{4}$$

where

$$P(x) = \frac{Z_T}{2K_o} \int_0^x i_{SH}(u)\, e^{+\Gamma_o u}\, du$$

$$Q(x) = \frac{Z_T}{2K_o} \int_0^x i_{SH}(u)\, e^{-\Gamma_o u}\, du$$

and

A, B, C_1, C_2 are constants fixed by boundary conditions

$K_o \equiv$ characteristic impedance of 0.375" diameter coax

$K_{SH} \equiv$ characteristic impedance of shield-earth line

*E. D. Sunde, "Earth Conduction Effects in Transmission Systems," Dover Publications, New York, N. Y., Chapter 1, pages 14-17.

Next, one must define the two cases outlined in the test.

Case 1 — There is a lightning flash to the cable shield at a point between main stations but the cable is not crushed.

Case 2 — Same as Case 1, but only the coaxial tube of interest is shorted at the point where the flash enters the shield.

The solutions for $i_o(x)$ — the current in the center conductor of the coax — are very complex algebraically and their derivation is tedious. I shall outline the procedure for Case 1 and simply write the solution for Case 2.

Refer to Figure AI-1. Note the zero position and positive direction of the x-axis: $x = 0$ is the point where the lightning flash enters the cable shield and the positive x-direction is to the right. The left-hand main station is located at $x = -L_2$ meters. Applying boundary conditions at $x = 0$ and at the main station, separate solutions for the shield-earth current for x positive and x negative are found.

Valid for $x \geq 0$

$$\left\{ i_{SH_1}(x) = -\frac{I_L(\omega)\left(1 + r_2\right)}{2\left(1 - r_1 r_2\right)} \left(e^{-\gamma_{SH} x} - r_1 e^{\gamma_{SH} x}\right) \right. \tag{5}$$

Valid for $x \leq 0$

$$\left\{ i_{SH_2}(x) = -\frac{I_L(\omega)\left(1 + r_1\right)}{2\left(1 - r_1 r_2\right)} \left(r_2 e^{-\gamma_{SH} x} - e^{\gamma_{SH} x}\right) \right. \tag{6}$$

where

$I_L(\omega) \equiv$ frequency spectrum of the lightning current

$$r_{1,2} \equiv \left(\frac{Z_{MS} - K_{SH}}{Z_{MS} + K_{SH}}\right) e^{-2\gamma_{SH} L_{1,2}}$$

These expressions for $i_{SH}(x)$ are now substituted into P(x) and Q(x) and the integration is performed.

$$
\text{valid for } x \geq 0 \left\{
\begin{aligned}
P_1(x) &= \frac{Z_T I_L(\omega)\left(1 + r_2\right)}{4K_o\left(1 - r_1 r_2\right)\left(\gamma_{SH}^2 - \Gamma_o^2\right)} \left\{\left(\gamma_{SH} + \Gamma_o\right)\left[1 - e^{-\left(\gamma_{SH} - \Gamma_o\right)x}\right]\right. \\
&\qquad \left. + r_1\left(\gamma_{SH} - \Gamma_o\right)\left[1 - e^{+\left(\gamma_{SH} + \Gamma_o\right)x}\right]\right\} \\
Q_1(x) &= \frac{Z_T I_L(\omega)\left(1 + r_2\right)}{4K_o\left(1 - r_1 r_2\right)\left(\gamma_{SH}^2 - \Gamma_o^2\right)} \left\{\left(\gamma_{SH} - \Gamma_o\right)\left[1 - e^{-\left(\gamma_{SH} + \Gamma_o\right)x}\right]\right. \\
&\qquad \left. + r_1\left(\gamma_{SH} + \Gamma_o\right)\left[1 - e^{+\left(\gamma_{SH} - \Gamma_o\right)x}\right]\right\}
\end{aligned}
\right.
$$

$$
\text{valid for } x \leq 0 \left\{
\begin{aligned}
P_2(x) &= \frac{Z_T I_L(\omega)\left(1 + r_1\right)}{4K_o\left(1 - r_1 r_2\right)\left(\gamma_{SH}^2 - \Gamma_o^2\right)} \left\{\left(\gamma_{SH} + \Gamma_o\right) r_2 \left[1 - e^{-\left(\gamma_{SH} - \Gamma_o\right)x}\right]\right. \\
&\qquad \left. + \left(\gamma_{SH} - \Gamma_o\right)\left[1 - e^{+\left(\gamma_{SH} + \Gamma_o\right)x}\right]\right\} \\
Q_2(x) &= \frac{Z_T I_L(\omega)\left(1 + r_1\right)}{4K_o\left(1 - r_1 r_2\right)\left(\gamma_{SH}^2 - \Gamma_o^2\right)} \left\{\left(\gamma_{SH} - \Gamma_o\right) r_2 \left[1 - e^{-\left(\gamma_{SH} + \Gamma_o\right)x}\right]\right. \\
&\qquad \left. + \left(\gamma_{SH} + \Gamma_o\right)\left[1 - e^{+\left(\gamma_{SH} - \Gamma_o\right)x}\right]\right\}
\end{aligned}
\right. \tag{7}
$$

Now, the voltage and current on the center conductor-shield line are related by the power converter input impedance at $x = L_1$ and $-L_2$.

One can find $i_o(x)$ for $x \geq 0$. By symmetry, we need not consider $i_o(x)$ for $x \leq 0$.

$$
\begin{aligned}
i_o(x)\Big|_{\text{case 1}} = \Bigg[&\Bigg(\left(\frac{1}{1 - R_1 R_2}\right)\Big\{R_1 R_2\left[P_1\left(L_1\right) - Q_1\left(L_1\right)\right] - P_2\left(-L_2\right) + R_2 Q_2\left(-L_2\right)\Big\} \\
&+ P_1(x)\Bigg) e^{-\Gamma_o x} - \Bigg\{\left(\frac{R_1}{1 - R_1 R_2}\right)\Bigg[P_1\left(L_1\right) - P_2\left(-L_2\right) - \frac{1}{R_1} Q_1\left(L_1\right) \\
&+ R_2 Q_2\left(-L_2\right)\Bigg] + Q_1(x)\Bigg\} e^{+\Gamma_o x}\Bigg]
\end{aligned} \tag{8}
$$

where

$$R_{1,2} \equiv \frac{Z_{pc} - K_o}{Z_{pc} + K_o} e^{-\Gamma_o 2L_{1,2}} \tag{9}$$

In an analogous manner, the somewhat simpler expression for $i_o(x)$ under Case 2 may be found. As in the previous case, $i_o(x)$ is valid for $x \geq 0$.

$$i_o(x)\Big|_{\text{case 2}} = \left\{ \left[\frac{Q_1(L_1) - R_1 P_1(L_1)}{1 + R_1} + P_1(x) \right] e^{-\Gamma_o x} - \left[\frac{R_1 P_1(L_1) - Q_1(L_1)}{1 + R_1} + Q_1(x) \right] e^{+\Gamma_o x} \right\} \tag{10}$$

Appendix II
Transmission Line Parameters

The equations for current in the center conductor of a coax tube of the L-5 cable were derived in Appendix I. This current depends on K_o, Γ_o, K_{SH} and γ_{SH}, the transmission line parameters used for the coupled lines. In this appendix are presented the frequency dependent expressions used for these parameters and some of the reasons that went into the choice of the specific models used in calculations.

The parameters for the coax transmission line are straightforward and are well documented. However, most documentation estimates these parameters for frequencies above 100 kHz, whereas our interest will center on frequencies of less than 10 kHz. Also, we must alter the homogeneous line parameters to account for the repeater impedance which appears every mile across the coaxial conductors. A low frequency equivalent circuit for the repeater is shown in Figure AII-1. Because our simplified coupled transmission line model assumes homogeneous lines, we shall distribute the repeater circuit parameters over each mile of line, thus modifying the primary line constants R, L, G, C. Henceforward, we shall consider only these modified primary constants and a homogeneous transmission line.

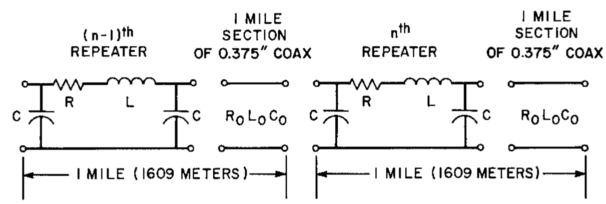

Figure AII-1a. Actual periodically terminated 0.375" coaxial circuit.

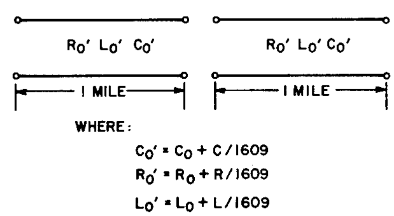

Figure AII-1b. Low frequency approximation to above.

For frequencies below 10 kHz, we have:

$$R \cong 3.4 \times 10^{-3} \text{ ohms/meter}$$

$$G \leq 3.1 \times 10^{-11} \text{ mhos/meter}$$

$$C \simeq 18.6 \times 10^{-11} \text{ farads/meter}$$

$$L \simeq 4.3 \times 10^{-7} \text{ henries/meter}$$

and the secondary constants

$$k_o \equiv \sqrt{\frac{R + j\omega L}{j\omega C}} \cong \left(0.23 \times 10^4 - j\,\frac{0.18 \times 10^8}{\omega}\right)^{1/2}$$

$$\Gamma_o \equiv \sqrt{(R + j\omega L)\,(j\omega C)}$$

$$\simeq \left(-\,\omega^2 \times 0.80 \times 10^{-16} + j\omega \times 0.63 \times 10^{-12}\right)^{1/2} \tag{1}$$

k_o and Γ_o are plotted in Figure AII-2 from 1 to 10^4 Hertz.

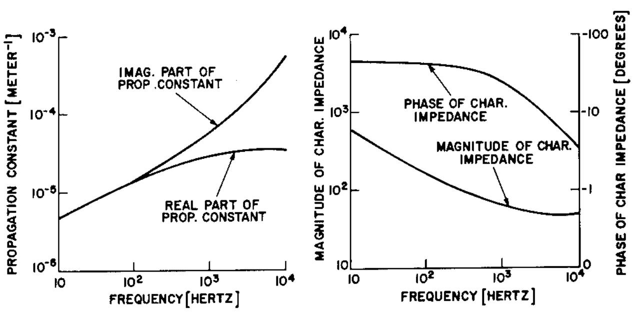

Figure AII-2. Propagation constant and characteristic impedance of low frequency approximation to periodically terminated 0.375" coax (refer to Fig. AII-1b).

The characteristics of the shield-earth transmission line are not at all obvious or straightforward. Before 1950, buried telephone cables were protected from lightning and other environmental hazards by a jute-covered lead shield. Within a few months after burial, the jute covering became soaked with water; from that time on, the lead shield could be considered to be in good electrical contact with the surrounding earth. Thus, current on the lead shield due to lightning flashes leaked off into the surrounding soil at a rate limited only by the soil conductivity and permittivity. In the 1940s, a reasonable model for the propagation constant of such a bare shield-earth transmission line was proposed and experimentally validated by E. D. Sunde.* His expressions for the transmission line parameters of a buried, bare shielded, cable are:

$$\gamma_{SH} \equiv \left[\frac{Z_i + \dfrac{j\omega\mu_{soil}}{2\pi}\ln\dfrac{1.85}{a\left(\gamma_{SH}^2 + \gamma_o^2\right)^{1/2}}}{\dfrac{1}{\pi\left(\sigma_{soil} + j\omega\varepsilon_{soil}\right)}\ln\dfrac{1.12}{\gamma_{SH}\,a}}\right]^{1/2}$$

$$k_{SH} \equiv \left\{\left[Z_i + \frac{j\omega\mu_{soil}}{2\pi}\ln\left(\frac{1.85}{a\left(\gamma_{SH}^2 + \gamma_o^2\right)^{1/2}}\right)\right] \times \frac{\ln\dfrac{1.12}{\gamma_{SH}\,a}}{\pi\left(\sigma_{soil} + j\omega\varepsilon_{soil}\right)}\right\}^{1/2} \tag{2}$$

where

$$\gamma_o^2 = j\omega\mu_{soil}\left(\sigma_{soil} + j\omega\varepsilon_{soil}\right)$$

σ_{soil} ≡ soil conductivity in [mhos/meter] generally ~ 10^{-2}

ε_{soil} ≡ soil permittivity in [farads/meter] generally ~ 10^{-10}

μ_{soil} ≡ soil permeability in [henries/meter] ($\cong \mu_o$)

Z_i ≡ shield surface impedance with external return [ohms/meter]

a ≡ shield radius [meters]

The parameters γ_{SH} and K_{SH} for a bare shield with the dimensions of the L-5 cable shield buried in a soil of conductivity 2.5×10^{-3} mhos/meter, permittivity $10 \times \varepsilon_{free\ space}$, and permeability equal to that of free space are plotted in Figures AII-3 and AII-4.

The multicoaxial cable proposed for the L-5 system possesses a lead shield and is covered by a 75-mil polyethylene jacket. This insulating shield cover greatly reduces the leakage of

*E. D. Sunde, "Lightning Protection of Buried Toll Cable," Bell System Technical Journal, Vol. 24, April 1945.

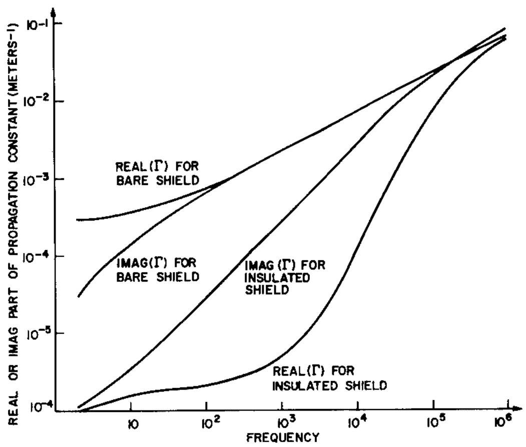

Figure AII-3. Real and imaginary parts of bare and insulated shield propagation constants for CLOAX 22 cable in

$$\sigma_{soil} = 2.5 \times 10^{-3} \text{ mhos/meter}$$

$$\varepsilon_{soil} = 10 \times \varepsilon_{freespace}$$

$$\mu_{soil} = \mu_{freespace}$$

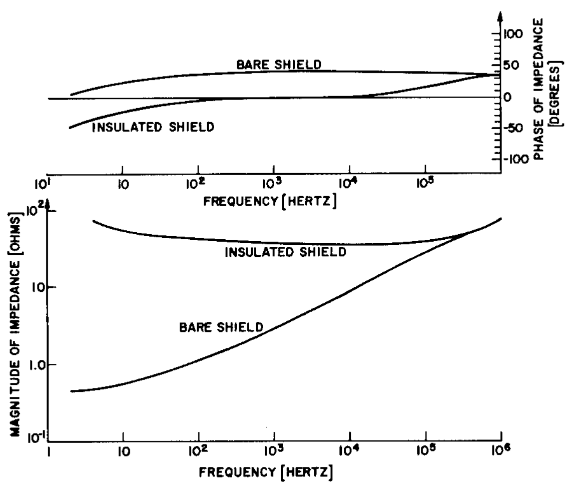

Figure AII-4. Characteristic impedance of shield-earth transmission line for bare and insulated shield.

$$\sigma_{soil} = 2.5 \times 10^{-3} \text{ mhos/meter}$$

$$\varepsilon_{soil} = 10 \times \varepsilon_{freespace}$$

$$\mu_{soil} = \mu_{freespace}$$

lightning current into the surrounding soil so long as it remains intact. If one does assume that the shield cover remains intact, several transmission line models are available. The various insulated shield models are in essential agreement, but the easiest expressions to evaluate for K_{SH} and γ_{SH} were developed by Marston and Graham.* Their model for propagation on a buried, insulated conductor allows fairly simple calculation of these parameters. The results are plotted in Figures AII-3 and AII-4, and the analytical expressions used to develop those graphs are:

$$\gamma_{SH} = \sqrt{Z \cdot Y}$$

$$K_{SH} = \sqrt{\frac{Z}{Y}}$$

where

$$Z \equiv Z_{SH} + j\,\omega\mu/2\pi \ln(1 + \delta/a)$$

$Z_{SH} \equiv$ shield surface impedance ω·external return

$a \equiv$ shield outer radius

$\delta \equiv \sqrt{2/\omega\mu_o\sigma_{soil}} \equiv$ skin depth in soil

$$Y \equiv Y_1 Y_2 / Y_1 + Y_2$$

$$Y_1 \equiv \pi\,(\sigma_{soil} + j\omega\varepsilon_{soil})/\ln[1 + \delta/(b + t)]$$

$t \equiv$ polyethylene shield cover thickness

$$Y_2 \equiv j\pi\omega\varepsilon_{poly}/\ln(1 + t/a)$$

where

$\sigma_{soil} \equiv$ soil conductivity in [meter-ohms]

$\varepsilon_{soil} \equiv$ soil permittivity in [farads/meter]

$\mu_{soil} \equiv$ soil permeability in [henries/meter]

In the calculation of L-5 diode current surges, it was found that the insulated shield model yielded significantly higher estimates of peak power and total charge than did the bare shield model. Figure AII-5 shows the diode current for a single current stroke of 1 kamp peak for each model.

*D. R. Marston and W. R. Graham, "Currents Induced in Cables in the Earth by a Continuous Wave Electromagnetic Field," Tech. Rep. AFWL-TR-65-94, May 1966.

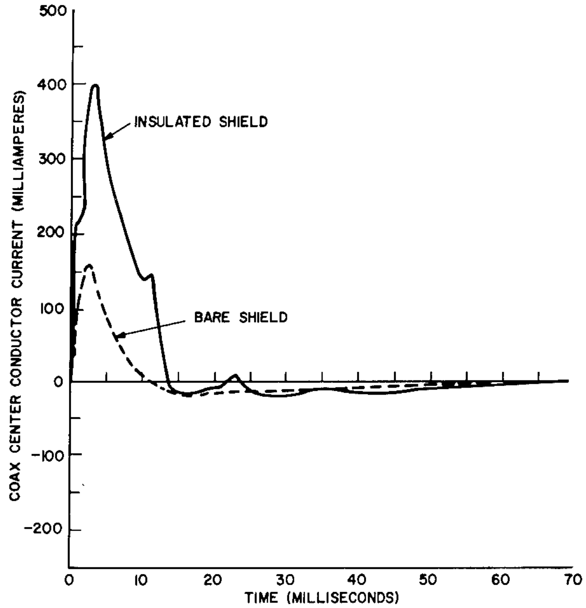

Figure AII-5. Comparison of coax center conductor current for bare and insulated shield-earth return models. A single lightning stroke hits the cable 2 km from a main station. A crush of the cable is assumed. The peak lightning current is 1100 amperes.

Considering the large difference in predicted current surges for the coaxial center conductors of the L-5 cable, it is obvious that a choice must be made between the two models.

Choosing between the insulated or bare shield models must depend on the magnitude of the shield current of interest and upon its frequency content. Lightning stroke currents of concern here have peak currents (I_0) of the order of tens of kiloamperes, and most of the energy associated with the stroke current is contained in frequencies less than 100 kHz.

I have chosen the bare shield model for the following reasons:

1. For peak currents of the order of tens of kiloamperes and a surge impedance of tens of ohms, shield earth voltages of the order of hundreds of kilovolts peak are developed. For frequencies below 100 kHz, most of this voltage appears across the shield cover (dielectric strength < 100 kvolts) and dielectric breakdown (pinholes) appear to be a necessary result. As a result of such pinholes in the shield cover, one may show analytically that the shield earth current behaves as though the shield were bare for lightning stroke currents of more than a few kiloamperes peak.*
2. At Bell Laboratories field laboratory, Chester, N. J., tests recently conducted on a buried insulated wire and on a buried insulated-shield cable indicate that current surges of tens of microseconds duration propagate as though the shield or wire were bare for peak currents of greater than 1 kiloampere, verifying thereby the prediction stated in 1. above.

It is thus apparent that a bare shield propagation model is indicated for lightning stroke currents greater than a few kiloamperes for the L-5 cable.

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*See Reference 3, Chapter 9.

ELECTROMAGNETIC INTERFERENCE WITH VIDEO TRANSMISSION CABLE

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SUMMARY

This report shows how to calculate the power of induced interference at cable end caused by its height from ground, earth conductivity, earthing resistance, radio wave angle to cable, etc., when interference wave progressing direction and intensity are given.

It takes into account the fact that cable shielding acts as wave antenna to radio frequency wave.

1. INTRODUCTION

Recently there is a strong demand for transmitting, via balanced type cable or coaxial cable, the signals of TV telephones, ITV, and data transmission in video frequency bands. As source of interference in such frequency bands can be mentioned power lines, various kinds of induction heaters, motors, automobiles, electric waves, and so forth. In this report an enquiry is made into the induction mechanism of the wave induction noise of the picture transmission balanced type and coaxial cables installed at aerial parts.

As the factors which affect the volume of induction noise we may take into consideration the intensity of the electric power of broadcasting wave, the frequency of broadcasting wave, the angle of oncoming broadcasting wave to the cable, the kinds of cable, the existence or otherwise of cable shielding, the coupling of the longitudinal circuit and real circuit of the cable, the strung-up and earthing conditions of the cable, earth electrical conductivity, etc. In this report we seek calculating formulas taking those factors into account and show that they nearly agree with the results of actual measurements, and indicate the limit under which, from the standpoint of induction interference, the existing cables can be used for video transmission ones, and also make a proposal regarding a video transmission cable, together with data on the design of the new cable.

2. METHOD FOR CALCULATING INDUCTION INTERFERENCE ELECTRIC POWER OF BROADCASTING WAVE

The video transmission cable is subjected to the induction from the broadcasting wave chiefly at aerially installed sections.

In proceeding with the calculatins, we will conceptually explain a route under which "balanced type cable with shielding" has its real circuit affected by induction noise from the broadcasting wave.

As shown in Fig 1, a broadcasting wave, which has entered at an angle of θ with an installed cable, induces an induced current of i (x) between cable shielding and earth, which current, under a transfer surface impedance Zks of the shielding, causes a longitudinal current $i_{\ell}(x)$ between shielded conductors. As the transverse circuit is not perfectly balanced, an induced voltage Vt (x) is created by $i_{\ell}(x)$. Below we will explain in consequential order.

2-1 Induced current in longitudinal circuit between pair and sheath

As the broadcasting wave is a vertically polarized one, it receives induction at the vertical portion of the cable; besides, since the earth is no complete electrical conductor, there arises a horizontal component in the electric field, and the wave receives induction also at the horizontal portion of the cable.

2-1-A Induced current in sheath - ground circuit by vertical electric field

As shown in Fig 2, induced current iv (x) in the circuit between cable sheath and ground by the vertical component Ev of the electric field is obtained. A parallel source is induced between cable and earth by Ev, and its value is Ev·h. At x = ξ point, since the current flows reversely, the electromotive forth is equal to zero.; so that at both (x=0, and x=l) ends, induced voltage is Ev·h1 and Ev·h2 ; therefore, we can calculate the current at x=x point. First, current i_{v1} (x) at x point by $Ev \cdot h_1$ becomes :

$$i_{v1}(x)=\frac{E_v \cdot h_1}{Z_1+Z} e^{-\gamma x}+\frac{E_v h_1}{Z_1+Z}\Gamma_2 \frac{e^{-\gamma(2\ell-x)}+\Gamma_1 e^{-\gamma(2\ell+x)}}{1-\Gamma_1\Gamma_2 e^{-2\gamma\ell}} \quad (1)$$

where

$$\Gamma_1=\frac{Z_1-Z}{Z_1+Z} \qquad \Gamma_2=\frac{Z_2-Z}{Z_2+Z}$$

Current $i_{v2}(x)$ at x point by $Ev \cdot h_2$ becomes :

$$i_{v2}(x)=\frac{-E_v \cdot h_2}{Z_2+Z}\left[e^{-\gamma(\ell-x)}-\Gamma_1 \cdot \frac{e^{-\gamma(\ell+x)}+\Gamma_2 e^{-\gamma(3\ell-x)}}{1-\Gamma_1\Gamma_2 e^{-2\gamma\ell}}\right] \cdot e^{-j\beta_0 \cos\theta \cdot \ell} \quad (2)$$

Therefore,

$$i_v(x)=i_{v1}(x)+i_{v2}(x) \quad (3)$$

2-1-B Induced current in the sheath-ground circuit by horizontal electric field

As shown in Fig 3, we will obtain the induced current $i_v(x)$ in the circuit between cable sheath and earth by the horizontal component E_H of electric field. The horizontal component E_H is obtained through the following equation :

$$E_H=E_v \cdot [60 q \lambda_0]^{-\frac{1}{2}} \quad (4)$$

where q : earth conductivity

λ_0 : free space wave length

Ev : Vertical component of the electric field

In an elementary length $d\xi$ of the sheath section, an electromotive force

$$E_\xi \cdot d\xi=E_H \cos\theta \cdot \exp[-j\beta_0 \cos\theta \cdot \xi] \cdot d\xi \quad (5)$$

is created in series (constant voltage source with zero internal impedance). The current $i_h(x)$ that flows at x=x under this source becomes as follows, from a concept of reflection :

$$i_h(x)=\frac{E_H \cdot \cos\theta}{2Z}\left\{\int_0^x e^{-i\beta\cos\theta\cdot\xi} \cdot e^{-\gamma(x-\xi)} d\xi + \Gamma_2 \cdot \frac{e^{-\gamma(\ell-x)}+\Gamma_1 e^{-\gamma(\ell+x)}}{1-\Gamma_1\Gamma_2 e^{-2\gamma\ell}} \times \int_0^\ell e^{-j\beta_0\cos\theta\cdot\xi} \cdot e^{-\gamma(\ell-x)} d\xi + \int_x^\ell e^{-j\beta_0\cos\theta\cdot\xi} \cdot e^{-\gamma(\xi-x)} d\xi + \Gamma_1 \frac{e^{-\gamma x}+\Gamma_2 e^{-\gamma(2\ell-x)}}{1-\Gamma_1\Gamma_2 e^{-2\gamma\ell}} \times \int_0^\ell e^{-j\beta_0\cos\theta\cdot\xi} \cdot e^{-\gamma\xi} d\xi \right\} \quad (6)$$

2-1-C Induced current in longitudinal circuit

Induced current i (x) in sheath-ground circuit obtained under 2-1-A, 2-1-B becomes as follows :

$$i(x)=i_v(x)+i_h(x) \quad (7)$$

As shown in Fig 1, if the surface transfer impedance of shielding is taken as Zks, the unit electromotive force of the longitudinal circuit--$E\eta\, d\eta$ becomes as follows :

$$E_\eta d\eta=Z_{KS} \cdot i(\eta)\, d\eta \quad (8)$$

Therefore, the induced current $i_\ell(x)$ in the longitudinal circuit (circuit between pair and shielding) becomes as follows on condition that both ends of the eongitudinal circuit be matched :

$$i_\ell(x)=\frac{Z_{KS}}{2Z_\ell}\left[\int_0^x i(\eta) \cdot e^{-\gamma\ell(x-\eta)} d\eta+\int_x^\ell i(\eta) e^{-\gamma\ell(\eta-x)} d\eta\right] \quad (9)$$

where Z_1 : Characteristic impedance of longitudinal circuit

γ_ℓ : Propagation constant of longitudinal circuit

$$Z_K=R_K+(R_1+j\frac{\omega\mu_0}{4\pi})\tan^2\Theta \quad (10)$$

where R_k : Surface transfer impedance of metal tube

R_1 : Surface impedance of metal tube

Z_k : Surface transfer impedance of helical shield

Θ : Angle of helical shield to the cable

ω : Angle frequency

2-2 Induced current in the transverse circuit (Real circuit)

2-2-A Induced current in transverse circuit

Having obtained the current distribution $i_\ell(x)$ of the longitudinal circuit, we are going to get a transverse circuit current $i_t(x)$. If the conversion factor per unit length from longitudinal circuit to transverse circuit is taken as C_n, C_f, the transverse circuit current is

$$i_t(x)=\frac{1}{2}\sqrt{\frac{Z_\ell}{Z_t}}\left\{C_f\int_0^x i_\ell(\xi) e^{-\gamma_t(x-\xi)} d\xi - C_n\int_x^\ell i_\ell(\xi) e^{-\gamma_t(\xi-x)} d\xi\right\} \quad (11)$$

Therefore, the transverse circuit voltage $V_t(x)$ becomes

$$V_t(x)=Z_t \cdot i_t(x) \quad (12)$$

where

Z_t : characteristic impedance of transverse circuit

2-2-B Conversion factor between longitudinal circuit and transverse circuit

i) Generally speaking, "C" is determined by the geometrical size difference between two cores, the non-uniformity of material, and deviations from manufacturing standards, and by this we can judge the quality of the cable. We will mention a method by which we can experimentally and simply obtain "Cn, f".

Substantially speaking, Cn, f changes longitudinally. But assuming that it is uniform on an average, we measure $V_t(0)/V_1(0)$ at the circuit of Fig 4.

To obtain $V_t(0)$ theoretically,

from Fig 4,

$$V_t(0)=\frac{1}{2}\sqrt{\frac{Z_t}{Z_\ell}}\cdot V_\ell(0)\int_0^\ell C_n\cdot e^{-(\gamma_\ell+\gamma_t)x}\,dx \tag{13}$$

$$=\frac{1}{2}\sqrt{\frac{Z_t}{Z_\ell}}\cdot C_n\cdot V_\ell(0)\cdot\frac{1-e^{-(\gamma_\ell+\gamma_t)\ell}}{\gamma_\ell+\gamma_t}$$

therefore, it becomes

$$C_n=2\cdot\frac{V_t(0)}{V_\ell(0)}\sqrt{\frac{Z_\ell}{Z_t}}\cdot\frac{\gamma_\ell+\gamma_t}{1-e^{-(\gamma_\ell+\gamma_t)\ell}} \tag{14}$$

From the measurement of $V_t(0)/V_1(0)$ from formula (14) we can get "Cn" from the kinds of cables. This is illustrated in Fig 6.

ii) We can also obtain it as follows :

In Fig 5, the transverse circuit and longitudinal circuit are matched for a line which is actually affected by induction interference, and $V_1(0)$ and $V_t(0)$ are measured. Now, if the induction voltage distribution of the longitudinal circuit is taken as follows :

$$V_t(\tau)=E_{Hi}\cdot\cos\theta\cdot\varepsilon^{-j\beta_0\cos\theta\cdot\tau}\,d\tau \tag{15}$$

as for longitudinal circuit voltage distribution $\overline{V}_1(x)$, the same calculation as for the preceding item is made

$$\overline{V}_\ell(x)=\int_0^x V_i(\tau)\,e^{-\gamma_\ell(x-\tau)}\,d\tau+\int_x^\ell V_i(\tau)e^{-\gamma_\ell(\tau-x)}\,d\tau$$

$$=E_{Hi}\cdot\cos\theta\Big\{\varepsilon^{-\gamma_\ell x}\frac{(\gamma_\ell-j\beta_0\cos\theta)x-1}{\gamma_\ell-j\beta_0\cos\theta}$$

$$-\varepsilon^{\gamma_\ell x}\frac{\overline{\varepsilon}^{-(\gamma_\ell+j\beta_0\cos\theta)\ell}-\varepsilon^{-(\gamma_\ell+j\beta_0\cos\theta)x}}{\gamma_\ell+j\beta_0\cos\theta} \tag{16}$$

therefore, it becomes

$$\overline{V}_\ell(0)=-E_{Hi}\cdot\cos\theta\cdot\frac{\varepsilon^{-(\gamma_\ell+j\beta_0\cos\theta)\ell}}{\gamma_\ell+j\beta_0\cos\theta} \tag{17}$$

Similarly,

$$\overline{V}_t(0)=\frac{1}{2}C_n\cdot\sqrt{\frac{Z_t}{Z_\ell}}\cdot E_H\cdot\cos\theta\Big[\frac{1}{\gamma_\ell-j\beta_0\cos\theta}\Big\{\frac{\varepsilon^{-(\gamma_t+j\beta_0\cos\theta)\ell}-1}{-(\gamma_t+j\beta_0\cos\theta)}$$

$$-\frac{\varepsilon^{-(\gamma_t+\gamma_\ell)\ell}-1}{\gamma_\ell+\gamma_t}\Big\}-\frac{1}{\gamma_\ell+j\beta_0\cos\theta}\Big\{\frac{\varepsilon^{(\gamma_\ell-\gamma_t)\ell}-1}{\gamma_\ell-\gamma_t} \tag{18}$$

$$\times\varepsilon^{-(\gamma_\ell+j\beta_0\cos\theta)\cdot\ell}-\frac{\varepsilon^{-(\gamma_t+j\beta_0\cos\theta)\ell}-1}{\gamma_t+j\beta_0\cos\theta}\Big\}\Big]$$

Finally, it becomes

$$\frac{\overline{V}_t(0)}{\overline{V}_\ell(0)}\equiv C_n\cdot f(\gamma_\ell,Z_\ell,\gamma_t,Z_t,\ell,\theta) \tag{19}$$

and C can be obtained.

Also from formulas (14) and (19),

$$\frac{\overline{V}_t(0)}{\overline{V}_\ell(0)}=\frac{V_t(0)}{V_\ell(0)}\cdot\frac{\gamma_\ell+\gamma_t}{1-e^{-(\gamma_\ell+\gamma_t)\ell}}\cdot f(\gamma_\ell,Z_\ell,\gamma_t,Z_t,\ell,\theta) \tag{20}$$

and it shows the relationship between Vt (0), Vl (0), $\overline{V}_t(0)$, and $\overline{V}_1(0)$.

2-3 Correspondence with measured values

Numerical calculation is made of the results of all the foregoing items and comparison is made with measured values. The test cable is 250 m of the existing 0.65 mm 30 pair CCP-AP cable, and the parameter needed for calculation is as under :

Cable Shielding material		Al
"	thickness	0.2 mm
"	inner diameter	13 mm ϕ
Installation conditions		
	Altitude of cable from the ground	$h_1 = h_2 = 3.5$ m
	Angle with electric wave	θ change
	Earthing conditions	Both ends earthed
		One end "
		Both ends unearthed
	Earth conductivity	$g = 1.5 \times 10^{-3}$ ℧/m
Electric field strength		Ev = 100 dBμV/m
Frequency		1 MHz

Propagation constant of transverse circuit	γ_t	18.6 dB/km 33.1 rad/km
Characteristic impedance of transvers circuit	Z_t	105Ω
Propagation constant of longitudinal circuit	γ_1	18.0 dB/km 38.0 rad/km
Characteristic impedance of longitudinal circuit	Z_1	70Ω
Propagation constant of sheath - ground circuit sheath and ground		15.0 dB/km 30.0 rad/km
Characteristic impedance of sheath - ground circuit	Z	600 Ω

By putting the above constants into formula (9), the vertical circuit current of CCP-AP cable is obtained, and then longitudinal circuit induced power Pv, Ph is obtained in the following cases :

where Pv : Induced voltage by vertical electric field

Ph : " " " horizontal electric field

Case 1 Pv and Ph in case cable length is changed from 10 m to 2,000 m with both ends earthed (earthing resistance 1Ω), and $\theta = 0^{o}$. The calculation result is shown in Fig 7-1.

Case 2 Pv and Ph in case cable length is changed from 10 m to 2,000 m with both ends unearthed, and $\theta = 0^{o}$. The calculation result is shown in Fig 7-2.

Case 3 Pv and Ph in case the shielding on the measurement side is earthed while the other end is unearthed, and the cable length is changed from 10 m to 2,000 m, and $\theta = 0^{o}$. The calculation result is as per Fig 7-3.

Case 4 Change of P_h and Pv in case both ends are earthed and cable length 1=250 m and θ is changed from 0^{o} to 360^{o}. The calculation result is shown in Fig 8. And in case cable length 1 = 2,000 m also is shown.

When measured values are shown in Fig 7 - Fig 8, it becomes mark◎; it is known that the calculated values well agree with measured values.

2-4 Study of induced noise

As a theoretical formula of induced current has been obtained from 2-1 and 2-2, we will calculate values and study the effect of each of the factors which affect the induced noise, and describe how to reduce the induced noise.

2-4-A Source of induction

This is an important factor which determines Ev and Eh. Induced voltage or induced current increases in direct proportion to Ev and Eh. The induced noise of a strung-up cable is determined almost by Eh.

2-4-B Cable installation place, installation altitude and earthing method

Earth conductivity g determins the horizontal electric field component which constitutes the greater part of induced noise. The larger g become, the smaller the induction. Next, it is desirable that the cable should be laid in such a way that the angle θ which the broadcasting wave propagation direction forms with the cable may be a right angle. Earthing should be made at both ends in case a cable is 1 km or longer. The smaller the cable altitude from the ground becomes, the smaller the characteristic impedance of circuit made with cable sheath and earth grows and the larger the propagation constant becomes. So, the induced noise is reduced.

2-4-C Induced object

One repeater section for a video transmission cable is generally 2 km or so. If the cable becomes as long as that, the earthing conditions of cable shielding no longer has any effect. Shielding effect is expressed in terms of surface transfer impedance Zk. Naturally enough, the smaller Zks, the better, and the induced current or voltage is in direct proportion to Zks, What we should bear in mind here is that, as shown in formula (10), even though a metal shielding tape is applied longitudinally to the cable, if the cable is twisted at the time of installation, Zks increases due to the effect of θ of formula (10).

Next, as shown in formula (11), the transverse circuit induced current it (x) is in proportion to longitudinal circuit-transverse circuit coupling coefficient C; so that it is necessary to see that the cable is manufactured which has "0" coefficient.

3. CABLE FOR VIDEO TRANSMISSION

As for a base-band video transmission cable for TV telephones, etc., which is likely to be put to pratical use in the near future, there arise a problem of induction for an aerial section caused by radio broadcasting wave. For example, if Spp/Nrms ratio required is 40 db, cable attenuation is 20 dB/repeater section in broadcasting wave band, and the signal level is +5 dBm, the transverse circuit reception noise level must be not more than −55 dBm.

When the currently used telephone cable and a new type cable for video transmission are viewed from the above standpoint, let us consider to what extent this problem goes. In this case, as a transmission technique to improve S/N ratio, it may be considered to increase the signal level such as preemphasis. Here we assume that this means serves to increase it by 10 dB or so.

3-1 Already installed cable

As an already laid cable, we will take an example of the 0.2 mm thick Al shielded cable, which was used above as a calculation example.

Since the longitudinal circuit noise level at 1 MHz in 100 dBuV/m electric field is −35 dBm and the compensate term for the ratio of the longitudinal and transverse circuits is 25 dB from formula (20), the longitudinal circuit induction level comes out at −60 dBm, and if the electric field magnitude is 130 dBuV/m, so we cannot get the S/N ratio required. It is expected that the unshielded cable receives an induction noise higher than that. Thus, in the base-band video transmission of the already installed cable, especially in the strong electric field, the induction noise poses a problem.

Table 1-1, 1-2 shows measured values of the induction interference of 250 m of various kinds of the currently used cables. From the viewpoint of the reduction of induction interference as above mentioned, we wish to propose a cable having a smaller Zk and Cn, f.

3-2 New cable

If we take up a new pair type cable for video transmission and a single cable system, we consider that the cable will be a unit shielded type one in view of the restrictions on the near-end crosstalk between pairs for transmission to the both direction. Also from the standpoint of the restrictions on the far-end crosstalk between circuits in one and the same direction, the cable has to be produced with special attention to the balance of its pairs. These are very effective from the viewpoint of induction noise reduction, and will probably, we believe, lessen the effect as compared with the conventional cable. It is, therefore, desirable that the cable be given 0.2 mm aluminium shielding as conventionally used and additionally a unit shielding. As regards, however, the unit shield layer, a simple shielding of extremely thin metal tape is preferable if we take into account a low cable cost, an increased conductor space factor, and so forth. Especially when we consider its jointing, etc., the unit shielded cable can be used without earthing if it meets the requirements for crosstalk. Through calculation and actual measurement we have looked into how far this aluminium shield simple unit shielding would prove effective.

The mechanism of induction can be conceived as follows.

Current i (η) is induced in the circuit which consists of cable sheath shield and the ground, by the horizontal and vertical electric field components of the broadcasting wave, in the same way as already mentioned; this current causes a voltage $Z_{ks} \cdot i(\eta) \cdot d\eta$ at η point of the inner surface of the sheath shield. The current and voltage of the vertical circuit composed of the unit shield and the cable sheath shield become

$$-\frac{d V_m(\eta)}{d\eta} = i_m(\eta) Z_m - Z_{KS} \cdot i(\eta) = i_m(\eta) Z_m + f(\eta)$$
$$-\frac{d\, i_m(\eta)}{d\eta} = V_m(\eta)\, Y_m \qquad (21)$$

and, from that, the voltage and current at x point become

$$V_m(x) = e^{-\gamma_m x}\left[-\int_0^x \frac{1}{2} f(\eta) e^{\gamma_m \eta} d\eta + A\right] + e^{\gamma_m x}\left[-\int_0^x \frac{1}{2} f(\eta) e^{-\gamma_m \eta} d\eta + B\right]$$
$$i_m(x) = e^{-\gamma_m x}\left[-\int_0^x \frac{1}{2} Y_m f(\eta) e^{\gamma_m \eta} d\eta + Y_m A\right] \qquad (22)$$
$$e^{\gamma_m x}\left[-\int_0^x \frac{1}{2} Y_m f(\eta)\, e^{-\gamma_m \eta} d\eta + B\, Y_m\right]$$

where A and B: constants determined by end conditions. Next, by this i_m (x), a voltage is induced in the longitudinal circuit consisting of cable conductors and unit shield, via the coupling impedance Zku of the unit shield. The following current is induced in that vertical circuit :

$$i_\ell(x) = \frac{Z_{Ku}}{2 Z_\ell}\left\{\int_0^x i_m(\xi) e^{-\gamma_\ell (x-\xi)} d\xi + \int_x^\ell i_m(\xi) e^{-\gamma_m (\xi - x)} d\xi\right\} \qquad (23)$$

And consequently, the following current flows in the transverse circuit of the cable :

$$i_t(x) = C_f \int_0^x i_\ell(\xi) e^{-\gamma_t (x-\xi)} d\xi + C_n \int_0^\ell i_\ell(\xi)\, e^{-\gamma_t (\xi - x)} d\xi \qquad (24)$$

where Cn : coupling constant of the vertical and transverse circuits of the conductor. In actual practice, as measurement is taken at cable end,

$$i_t(0) = C_n \int_0^\ell i_\ell(\xi) e^{-\gamma_\ell \xi}\, d\xi \qquad (25)$$

can be obtained as a transverse circuit induced noise current.

By way of example, Fig 10 shows values of a cable sheath shield at the end and of the vertical circuit voltage of the cable, which are obtained by the above calculation, in respect to two earthing conditions ($Z_1 = Z_2 = \infty$, $Z_1 = Z_2 = 0$) ; $V = V_n(0) + V_\ell(0)$.

From Fig 10 it is clearly seen that the unit shield proves effective judging from the fact that, as regards the broadcasting wave induced noise in the case of unit shield type, the coupling impedance of the cable sheath is almost the same as the calculation examples of Fig 7-Fig 8. Measured values are shown in Fig 10 of 210 m long cable, and they very well agree with the calculated values.

From the above calculations and examples we can imagine that the londitudinal circuit induction level of the new cable in 1 MHz 100 dB V/m electric field strength will be −50 dBm with 2 km cable length. (Fig 10). The effect from the unit shield is in the vicinity of 15 dB. This can also be confirmed from an induction level difference between the video transmission pairs within the unit shield and the filler pairs outside the shield. Also it is to be inferred that the traverse circuit level will be −75 dBm because the compensate term for the ratio of the vertical and transverse circuits is −25 dB according to the result of substitution of measured values in formula (20). In an intense electric field of 130 dBmV/m or so, the transverse circuit induced power becomes −45 dBm, and it is barely possible to make video transmission by imposing an emphasis of 10 dB.

4. CONCLUSION

We summarize what we have explained in the foregoing, as under:

1) We have clarified the mechanism of induction interference from broadcasting wave of an aerially installed shielded balanced type cable; namely, the energy of the wave is converted into induction electromotive force at a circuit consisting of cable shield and the ground, and induced at the vertical circuit of the conductor via the surface transfer impedance of the shield, and is further converted to the transverse circuit by coupling coefficient.

2) As mentioned in the Introduction, we have obtained those formulas which give induction electric power output as a function of factors in affecting induction interference. They have clarified the extent of the effects of various factors and made estimated calculation possible. This method is also applicable to an aerially installed coaxial cable.

3) As a result of calculation and actual measurement of the induction noise to the existing balanced type cables by broadcasting wave, we have shown that CCP-P type cable and CCP-AP type cable have no problem in an intense electric field of usual case but are unfit for video transmission in the strong electric field and that a unit shield type LAP type cable which has an improved coupling between vertical and transverse circuits answers the purpose.

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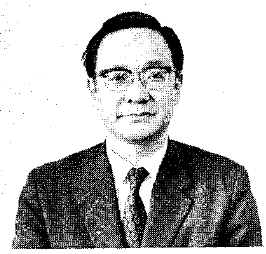

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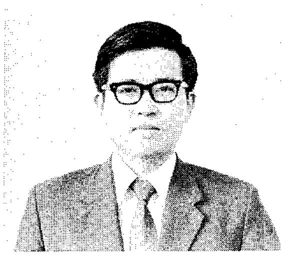

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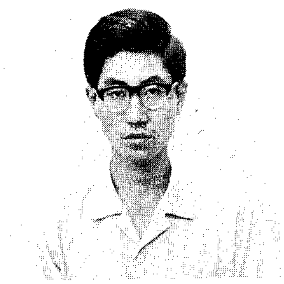

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Graduating from Tohoku University in 1969, Mr. Hondo entered The Furukawa Electric Co., Ltd., and engaged in research in broadband transmission balanced type cable at the company's Research Section.

Fig 1. The mechanism of induction on traverse circuit of cable from the broadcasting wave

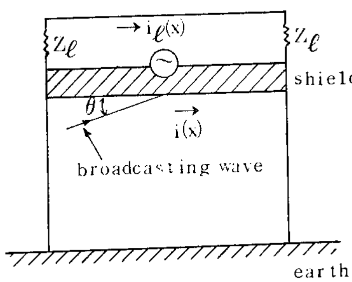


Fig 2. Induced current by virthical electric field under condition h1-h2 ℓ

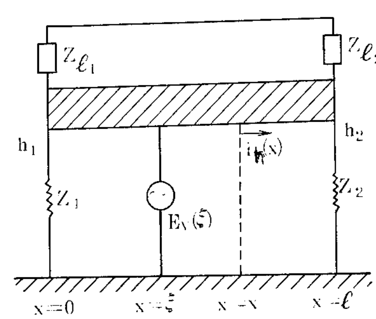


Fig 3. Induced current by horizontal electric field

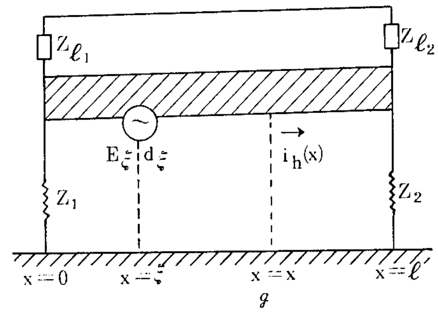


Fig 4. Measuring method of conversion factor between longitudinal circuit and transverse circuit

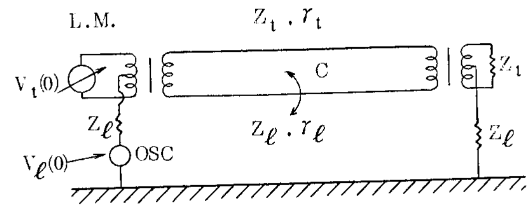


Fig 5. Coupling with distribution wave source

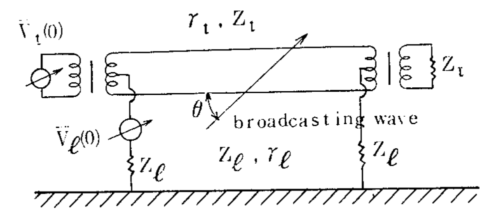


Fig 6. An example of compensate curve

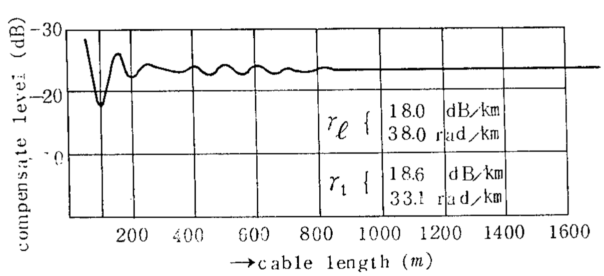


Table 1－1 Measurement of the induction noise to the transverse circuit of the existing balansed type cable

(Normarized maximum strength of electric field to 100dBμV/m)

dBm $\ell = 250m$ $Z_1 = Z_2 = 0$

Cables / Frequency	0.9㎜ 30pairs Intercity CCP−P	0.65㎜ 30pairs Intercity CCP−AP	0.4㎜ 400pairs Intercity star stalpeth	Unit shielded 0.65㎜ Video pairs within units	type LAP cable 0.5㎜ Filler pairs out of unit
590KHz	−60.5 (12.0)	−94.5 (3.0)	< −116.9 (2.3)	< −113.4 (5.8)	− 98.5
690	−63.1 (6.9)	−95.9 (4.3)	< −102.9 (4.9)	−101.7 (12.3)	− 99.8
810	−63.0 (7.6)	−87.9 (3.9)	< −108.7 (0.7)	< −103.5 (5.4)	− 90.0
950	−61.9 (4.3)	−88.5 (5.2)	< −106.3 (2.4)	< −101.3 (8.4)	− 95.3
1130	−71.3 (4.5)	−97.9 (3.9)	< −112.4 (3.9)	−110.6 (11.5)	−105.9
1310	−76.3 (8.6)	−97.9 (2.8)	< −120.4 (2.4)	< −109.4 (8.3)	−111.5
Number of samples	15	10	12	10	2

( ) Standard deviation But CCP−P have no shield

Table 1－2 Measurement of the induction noise to the vertical circuits of the existing balansed type cables

(Normarized maximum strength of electris field to 100 dBμV/m)

dBm $\ell = 250m$ $Z_1 = Z_2 = 0$

Cables / Frequency	0.9㎜ 30 pairs Intercity CCP−P	0.65㎜ 30pairs Intercity CCP−AP	0.4㎜ 400 pairs Intercity star stalpeth	Unit shielded 0.65㎜ Video pairs within units	type LAP cable 0.5㎜ Filler pairs out of unit
590KHz	− 9.6 (2.4)	−40.6 (3.0)	−74.5 (1.3)	−71.3 (2.3)	−37.9
690	−16.3 (1.0)	−39.6 (4.3)	−66.6 (6.1)	−65.2 (4.3)	−38.1
810	−17.6 (0.8)	−37.1 (1.2)	−76.8 (2.1)	−60.7 (1.5)	−44.3
950	−16.1 (0.5)	−34.4 (0.5)	−66.0 (1.9)	−56.9 (0.3)	−35.8
1130	−19.4 (0.3)	−40.8 (0.2)	−70.0 (1.1)	−70.0 (0.3)	−42.9
1310	−30.6 (1.3)	−45.2 (0.4)	−86.7 (2.0)	−69.5 (1.1)	−49.3

( ) Standard deviation But CCP−P have no shield

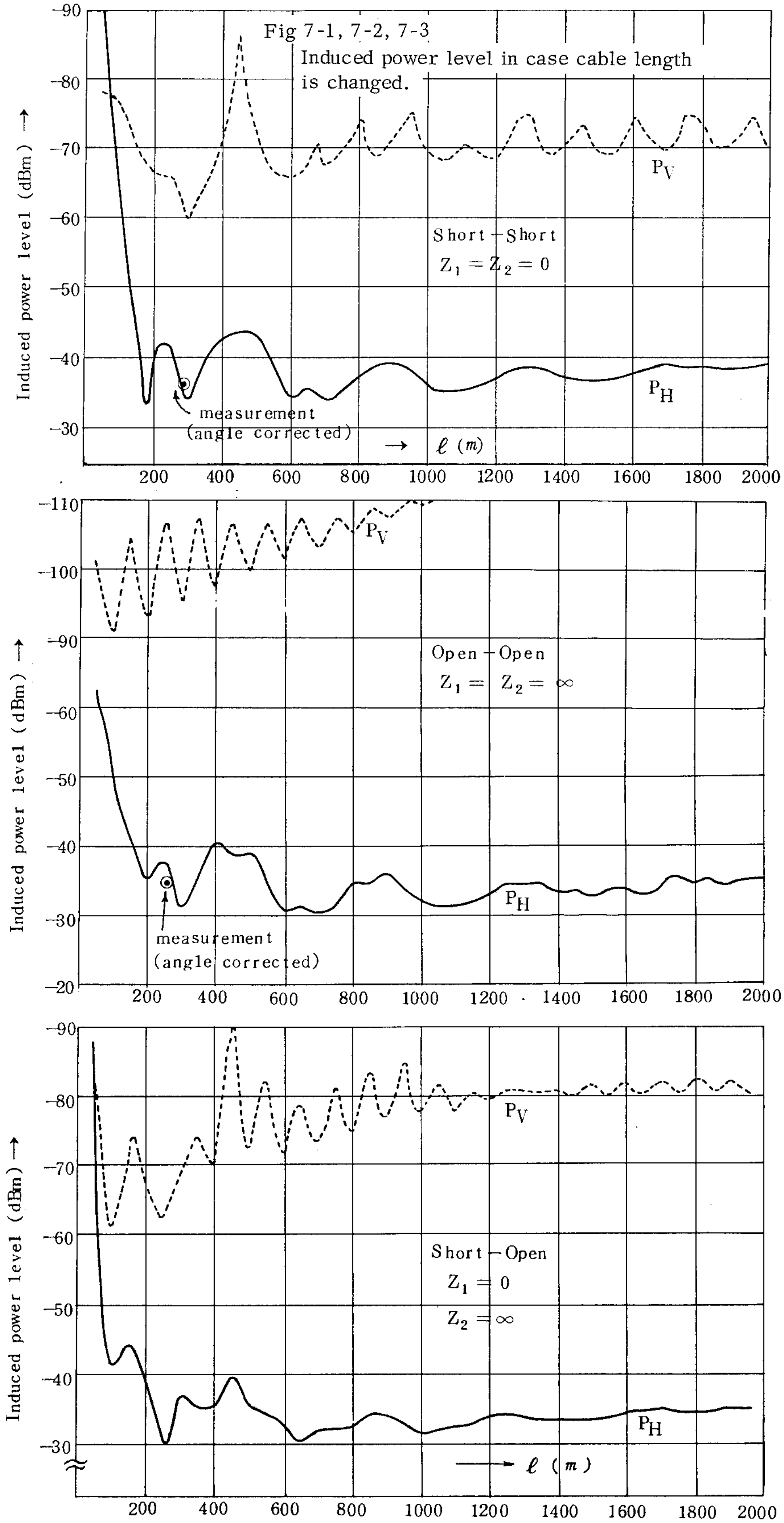


Fig 7-1, 7-2, 7-3
Induced power level in case cable length is changed.

Fig 8. Induced power level in case the angle of broad-casting wave direction to cable is changed.

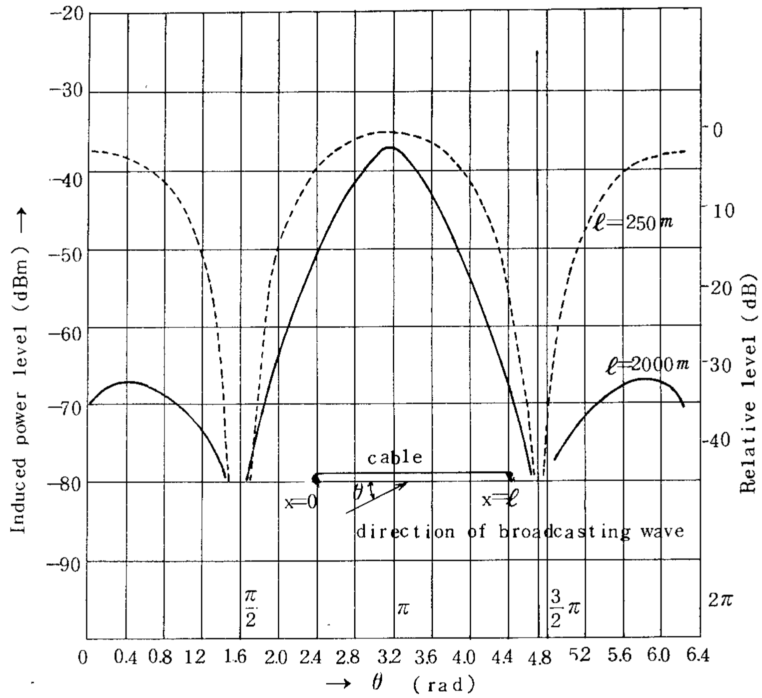


Fig 9. Mechanism of Induction for Unit shielded cable

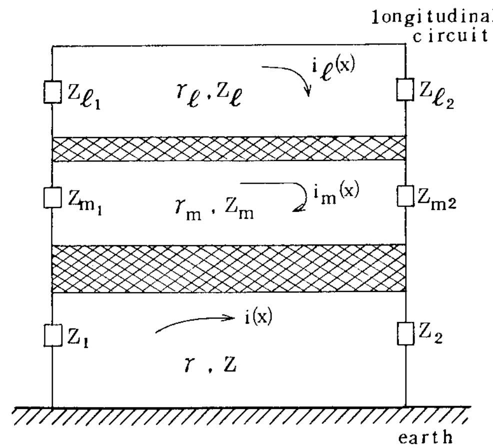
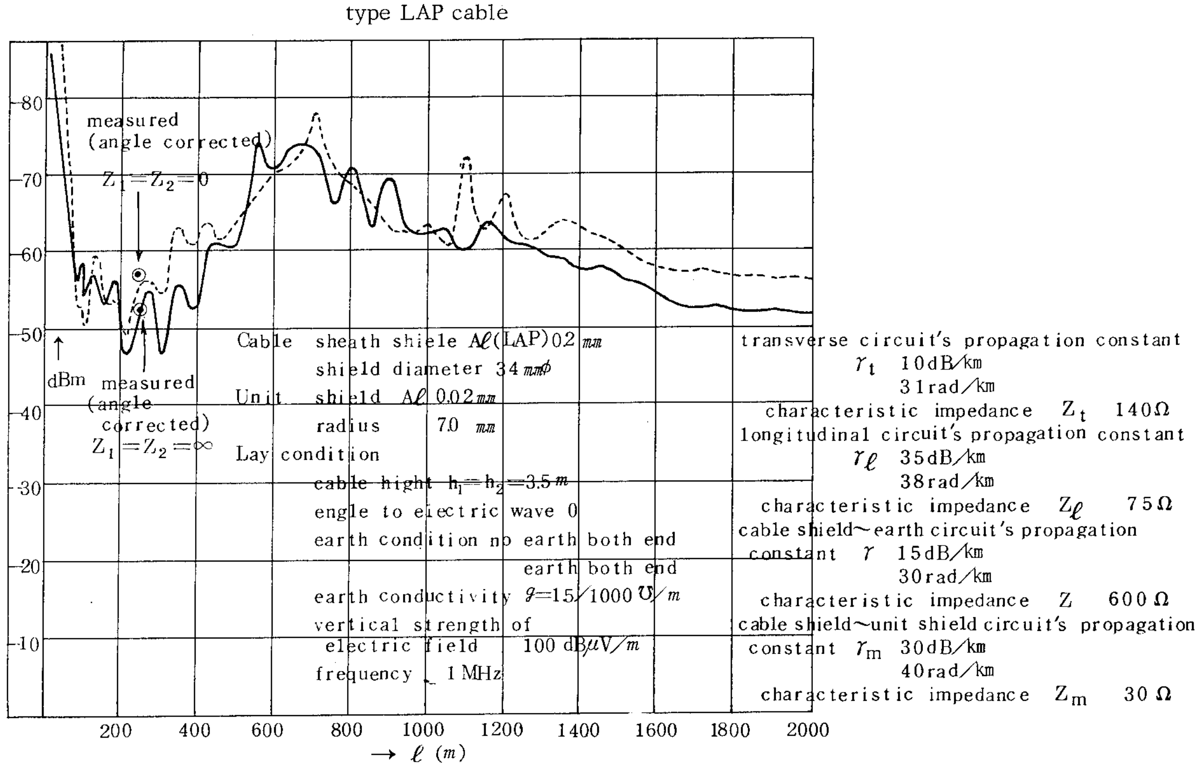


Fig 10. Induction interference level of shielded unit type LAP cable



COMPUTER AIDED DESIGN OF BRAID PARAMETERS FOR COAXIAL CABLE

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INTRODUCTION: Shielding of coaxial cable as well as other special multi-conductor cable designs is becoming increasingly important to minimize electromagnetic radiation from or into the cable. Digital data transmission, broadband radio frequency circuits, sensitive audio or voice circuits, as well as high intensity voltages such as lightning or electromagnetic pulse (EMP) have established requirements for better shielding of cable. For cables whose application requires a high degree of flexibility (ease of bending and/or long flex life), braided conductors are frequently used in the cable design.

The cable design engineer who must establish the specification for the braid is faced with optimizing the design in regard to its shielding effectiveness, weight and cost, attenuation, and its flexibility. In order to provide the cable engineer with a tool to aid him in selecting a design, a computer program (Fortran IV) was developed for the enclosed series of tabular data which could be readily used to determine the physical parameters of the braid, as well as information to judge its potential flexibility and attenuation characteristics.

CALCULATIONS: Before discussing the data in the tables, a brief review is given of the braid elements and the formulas used to calculate the various parameters.

Figure 1 schemtacially illustrates the elements of a braid design on a circular cable core which could represent the dielectric of a coaxial cable, or a stranded multi-conductor core, or a single insulated wire. The formulas for calculating the various braid parameters are derived from Figure 2 and are given by:

(1) $C = (2F - F^2) \times 100$
(2) $F = PNd/\sin A$
(3) $A = \tan^{-1} 2\pi(D + 2d)\ P/C$
(4) $W = (2\ \ D/d)\ Fw$
(5) $\alpha_c = C\left[(K_s/d) + (K_b/D)\right]\sqrt{f}$
(6) $K_b = 1.0/F \cos^2 A$

where:

- C = percentage of area of cable surface covered by braid
- F = fill factor (space or weight factor)
- A = angle of braid wire with cable axis
- D = diameter over cable core
- d = strand (or braid wire) diameter
- P = picks per inch
- C = number of carriers
- N = number of ends (braid wire) per carrier
- W = weight of braid per unit length
- w = weight of strand (braid wire) per unit length
- K_b = braiding factor which is used for attenuation calculations
- α_c = attenuation of copper conductors in coaxial cable
- C = constant for a given conductor material and cable impedance

TABULAR DATA: For a specified number of carriers, ends per carrier, and picks per inch, each table includes the coverage, fill factor, angle, and braiding factor as the strand diameter and diameter over dielectric is varied. There are forty-five such tables for each combination of 5 carriers (12, 16, 24, 36, 48), 3 picks per inch (3, 9, 15) and 3 ends per carrier (4, 7, 10). The strand diameters range from 0.003 to 0.010 inches and the diameter over dielectric range from 0.050 to 1.000 inches. These values are considered quite practical for most cable designs and interpolation or approximation can be easily made for any other combination of braid parameters. To provide data for smaller intervals within the range of ends and picks would result in an excessive number of tables. (For example, if the number of intervals were increased from 3 to 5 for the ends and picks, we would have 125 tables).

In using the tables, the following qualifications should be noted:

(a) The asterisk indicates that the coverage exceeds 100% or the braiding factor is less than 1, and is therefore not a realistic braid design. One-hundred percent coverage or braiding factor equal to 1 is equivalent to a solid conductor and a braid cannot be better than a solid conductor.

(b) Coverage of 100% in the table is the result of rounding off of the decimal to the nearest tenth, i.e., when the coverage is equal to or greater than 99.95%, it is printed out of the computer as 100.0%.

(c) The calculations are based on a tight braid design (i.e., mean diameter equal to D + 2d), and no allowance was made for air space or looseness. For larger size cables, it may be more accurate to use a mean diameter of (D + 3d) instead of (D + 2d). The data in the tables are limiting values and practical cables would actually have slightly lower coverage than those indicated because of manufacturing tolerances and variations.

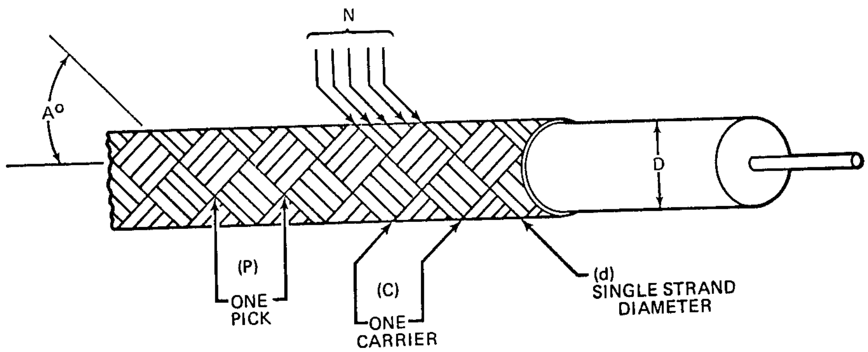
(d) The weight of the braid is not given in the table since the density or weight of the braid material must be known; however, it can be readily calculated from equation (4) for any specified braid material, strand diameter, and core diameter since the fill factor for the braid is given in the table.

(e) The braiding factor is useful in calculating outer conductor or shield attenuation. It is a measure of the ratio of the lay factor to the fill factor. The lay factor is the ratio of the actual length of wire to the linear length of cable, therefore, the greater the lay factor the greater the braiding factor. In addition, the fill factor is a measure of the surface area covered by the braid, therefore the lower the fill factor, the greater the braid factor. It is therefore reasonably apparent that the longer the braid wire relative to the length of cable and the lower the fill factor, the greater will be the braiding factor and, in turn, the attenuation.

REFERENCE: Spicer, L. R., "Relationships Between Attenuation and Wire Braid Design for Flexible Radio Frequency Cables," Electrical Communication, Vol. 40, No. 4, 1965, pp 487-492

Jack Spergel was born in Brooklyn, New York, on September 3, 1924. He attended City College of New York from 1942 to 1943, and served in the U. S. Army Air Corps from 1943 to 1945. After World War II, Mr. Spergel attended Cornell University, Ithaca, New York, where he received a B.E.E. degree in 1949. He is a Senior Member of IEEE.

Since 1949, he has been employed at the Electronic Technology and Devices Laboratory, U. S. Army Electronics Command, Ft. Monmouth, N. J., where he has been engaged in research and development of coaxial transmission lines, wire and cable, and electrical connectors. For the past eight years, Mr. Spergel has been Chief, Transmission and Electromechanical Devices Branch, responsible for the development of cables and connectors for USAECOM and coordinating such activities within Dept. of Army and DOD. He is currently the Army Representative to NATO Special Working Group AC/67(SWG/12) on "Electrical Connectors and Connections." For the past eight years, he has been Co-Chairman of the International Wire and Cable Symposium, and served as chairman of a USAMC Ad-Hoc Committee on a Handbook for Electrical Wire and Cable (ANCP 706-125). Mr. Spergel has published over 15 technical papers on the subject of connectors and/or cable, and has recently written a chapter on Coaxial Transmission Lines for a McGraw-Hill Handbook on Wire and Cable to be published in the near future.

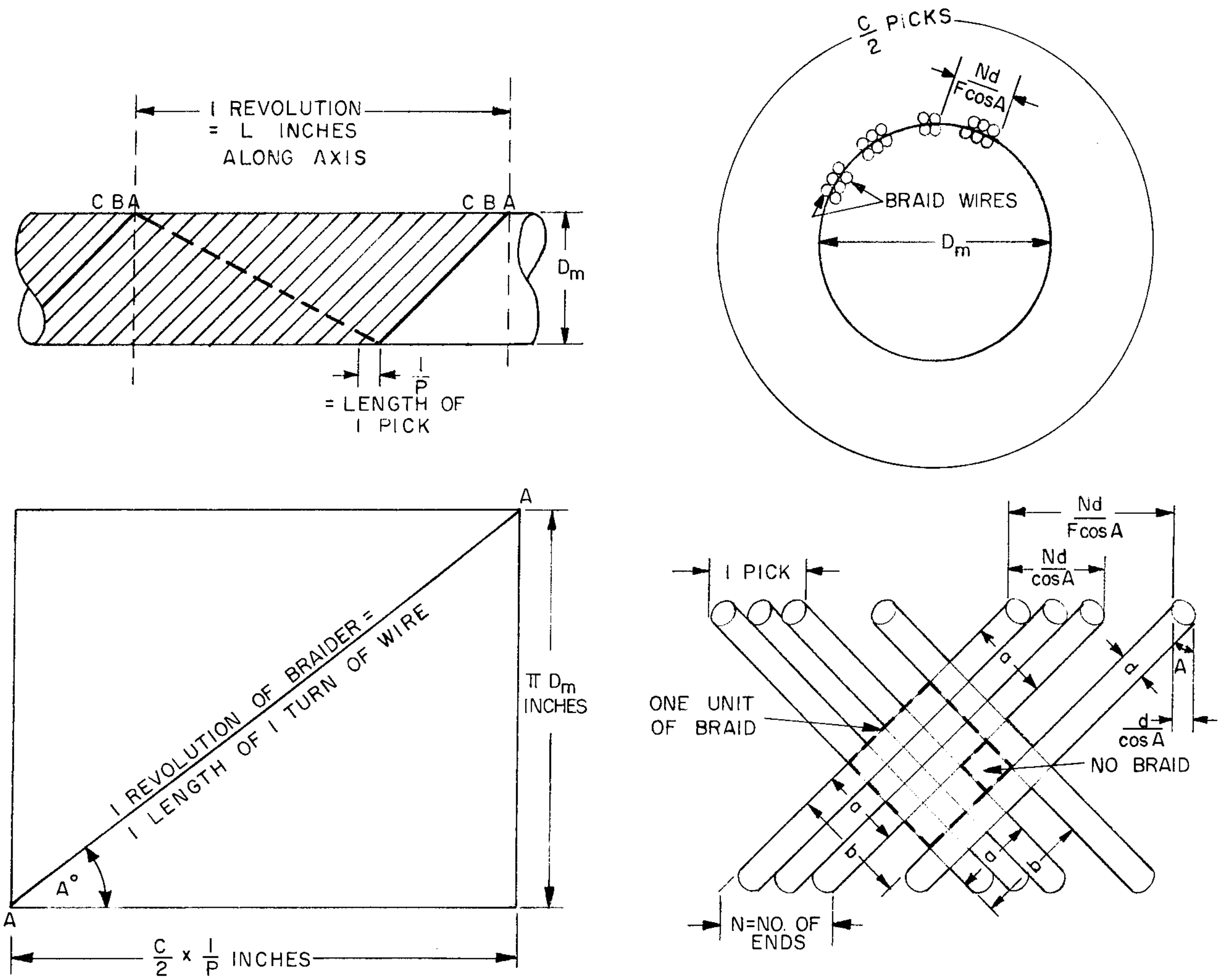


SHIELD-CONSTRUCTIONAL DETAILS

FIG. 1

FORTRAN IV COMPUTER PROGRAM FOR CALCULATING BRAID PARAMETERS

```
 FILE 6=OUTPT, UNIT=PRINTER
 REAL K(25),C(5),D(7),P(7),N(7),A(25),COV(25),DOD(25),F(25)
DATA C/12,16,24,36,48/,P/3,5,7,9,11,13,15/,
- N/4,5,6,7,8,9,10/,D/.003,.004,.005,.006,.007,.008,.010/
PI=4.*ATAN(1.)
 5 FORMAT(1H1,45X,"BRAID DESIGN PARAMETERS FOR COAXIAL CABLE")
 DO 100 KC=1,5,1
 CR=C(KC)
  DO 100 I=1,7,3
  PK=P(I)
  DO 100 J=1,7,3
  EN=N(J)
 WRITE(6,5)
  WRITE(6,10)
  10 FORMAT(1H0,50X,"CARRIERS     PICKS     ENDS")
  WRITE(6,15) CR,PK,EN
  15 FORMAT(1H ,53X,I2,10X,I2,7X,I2)
  WRITE(6,20)
  20 FORMAT(1H0,"STR.DIA.",20X,"DIAMETER OVER DIELECTRIC")
  WRITE(6,25)
  25 FORMAT(1H0,12X,"0.050 0.100 0.150 0.200 0.250 0.300"
 -" 0.350 0.400 0.450 0.500 0.550 0.600 0.650 0.700 0.750"
 -" 0.800 0.850 0.900 0.950 1.000")
  DO 100 L=1,7
  SD=D(L)
  DO 150 M=1,20
  DOD(M)=FLOAT(M)/20
 A(M)=(180./PI)*ATAN(2.*PI*(DOD(M)+2.*SD)*PK/CR)
  F(M)=PK*EN*SD/SIN(A(M)*PI/180.)
  COV(M)=(2.*F(M)-F(M)**2)*100
  K(M)=1.0/(F(M)*(COS(A(M)*PI/180.))**2)
  IF(F(M).LE.1.0)GO TO 150
   COV(M)=10E50
  K(M)=10E50
  150 CONTINUE
  WRITE(6,30)SD,(COV(M),M=1,20)
  30FORMAT(1H0,F6.3,3X,"%C",20F6.1)
  WRITE(6,55) (F(M),M=1,20)
  55FORMAT(1H ,10X,"F",20F6.3)
  WRITE(6,35) (A(M),M=1,20)
  35FORMAT(1H ,10X,"A",20F6.1)
  WRITE(6,40) (K(M),M=1,20)
  40FORMAT(1H ,10X,"K",20F6.2)
  100 CONTINUE
  STOP
  END
```



$D_m = (D + 2d)$ mean diameter

Length of lay $= C/2P =$ Number of picks x length of pick

$\tan A = \pi D_m/(C/2P) = 2\pi(D + 2d)P/C$

$A = \tan^{-1} 2\pi(D + 2d)P/C$

$F = a/b =$ fill factor, i.e., the ratio of the actual width of one pick to the width of one pick for 100% coverage

Width of one pick $= Nd/\cos A$

Number of picks $= C/2$

Average circumference $= \pi D_m = (Nd/F \cos A)(C/2)$

$\cos A = NdC/2\pi D_m F$

$(\cos A)(\tan A) = \sin A = (NdC/2\pi D_m F)(2\pi D_m P/C)$

$F = NdP/\sin A$

$$\% \text{ Coverage} = \frac{\text{actual area of braid}}{\text{total surface area}} \times 100$$

$$= \frac{b^2 - (b-a)^2}{b^2} = \frac{b^2 - b^2 + 2ab - a^2}{b^2}$$

$$\% \text{ Coverage} = \frac{2ab}{b^2} - \frac{a^2}{b^2} = 2\left(\frac{a}{b}\right) - \left(\frac{a}{b}\right)^2 = 2F - F^2$$

From Reference:

Braiding Factor, K_b, is ratio of lay factor K_l to fill factor, F.

Lay factor is defined as $K_l = 1 + \tan^2 A$

$K_b = K_l/F = (1 + \tan^2 A)/F$

$K_b = 1/F \cos^2 A$

FIG. 2

BRAID DESIGN PARAMETERS FOR COAXIAL CABLE

CARRIERS	PICKS	ENDS
12	3	4

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	65.3	39.0	28.0	22.0	18.4	15.9	14.2	12.9	12.0	11.2	10.6	10.2	9.8	9.5	9.2	9.0	8.8	8.6	8.5	8.3
	F	0.411	0.219	0.151	0.117	0.096	0.083	0.074	0.067	0.062	0.058	0.055	0.052	0.050	0.048	0.047	0.046	0.045	0.044	0.043	0.043
	A	5.0	9.5	13.8	17.9	21.9	25.7	29.2	32.5	35.6	38.5	41.1	43.6	45.9	48.0	49.9	51.7	53.4	54.9	56.3	57.7
	K	2.45	4.69	7.01	9.45	12.04	14.81	17.80	21.01	24.47	28.20	32.21	36.51	41.10	46.00	51.21	56.74	62.59	68.76	75.26	82.09
0.004	%C	77.8	49.2	35.9	28.5	23.9	20.8	18.6	17.0	15.8	14.8	14.0	13.4	12.9	12.5	12.1	11.8	11.6	11.4	11.2	11.0
	F	0.529	0.287	0.199	0.155	0.128	0.110	0.098	0.089	0.082	0.077	0.073	0.069	0.067	0.065	0.063	0.061	0.060	0.059	0.058	0.057
	A	5.2	9.6	13.9	18.1	22.1	25.8	29.4	32.7	35.7	38.6	41.2	43.7	45.9	48.0	50.0	51.8	53.4	55.0	56.4	57.7
	K	1.91	3.58	5.33	7.16	9.11	11.20	13.44	15.86	18.46	21.27	24.28	27.51	30.97	34.65	38.57	42.73	47.12	51.76	56.64	61.77
0.005	%C	87.0	58.1	43.2	34.6	29.2	25.5	22.9	20.9	19.4	18.3	17.3	16.6	16.0	15.5	15.0	14.7	14.4	14.1	13.9	13.7
	F	0.639	0.352	0.246	0.192	0.159	0.137	0.122	0.111	0.102	0.096	0.091	0.087	0.083	0.081	0.078	0.076	0.075	0.073	0.072	0.071
	A	5.4	9.8	14.1	18.3	22.2	26.0	29.5	32.8	35.9	38.7	41.3	43.8	46.0	48.1	50.0	51.8	53.5	55.0	56.4	57.8
	K	1.58	2.92	4.32	5.79	7.35	9.03	10.83	12.77	14.86	17.11	19.53	22.12	24.89	27.84	30.99	34.32	37.84	41.56	45.48	49.59
0.006	%C	93.4	65.8	49.9	40.4	34.3	30.0	27.0	24.7	23.0	21.7	20.6	19.7	19.0	18.4	17.9	17.5	17.1	16.8	16.5	16.3
	F	0.743	0.416	0.292	0.228	0.189	0.164	0.146	0.133	0.123	0.115	0.109	0.104	0.100	0.097	0.094	0.091	0.090	0.088	0.086	0.085
	A	5.6	10.0	14.3	18.4	22.4	26.1	29.6	32.9	36.0	38.8	41.4	43.9	46.1	48.2	50.1	51.9	53.6	55.1	56.5	57.8
	K	1.36	2.48	3.65	4.87	6.18	7.58	9.09	10.71	12.45	14.33	16.35	18.52	20.84	23.30	25.93	28.71	31.66	34.76	38.03	41.46
0.007	%C	97.4	72.6	56.0	45.8	39.0	34.4	31.0	28.4	26.5	25.0	23.7	22.7	21.9	21.2	20.7	20.2	19.8	19.4	19.1	18.9
	F	0.840	0.477	0.337	0.264	0.219	0.190	0.169	0.154	0.143	0.134	0.127	0.121	0.116	0.113	0.109	0.107	0.104	0.102	0.101	0.099
	A	5.7	10.2	14.4	18.6	22.5	26.3	29.8	33.0	36.1	38.9	41.5	44.0	46.2	48.3	50.2	52.0	53.6	55.1	56.6	57.9
	K	1.20	2.17	3.17	4.22	5.34	6.55	7.84	9.23	10.74	12.35	14.09	15.95	17.94	20.06	22.32	24.71	27.24	29.90	32.71	35.66
0.008	%C	99.5	78.4	61.6	50.8	43.6	38.5	34.8	32.0	29.9	28.2	26.8	25.7	24.8	24.0	23.4	22.9	22.4	22.0	21.7	21.4
	F	0.931	0.536	0.380	0.299	0.249	0.216	0.193	0.175	0.163	0.152	0.144	0.138	0.133	0.128	0.125	0.122	0.119	0.117	0.115	0.113
	A	5.9	10.3	14.6	18.7	22.7	26.4	29.9	33.2	36.2	39.0	41.6	44.1	46.3	48.4	50.3	52.0	53.7	55.2	56.6	57.9
	K	1.09	1.93	2.81	3.73	4.72	5.77	6.91	8.13	9.45	10.87	12.39	14.03	15.77	17.63	19.61	21.71	23.92	26.26	28.72	31.31
0.010	%C	******	87.6	71.4	60.0	52.0	46.3	42.1	38.8	36.3	34.3	32.7	31.4	30.4	29.5	28.7	28.1	27.5	27.1	26.6	26.3
	F	1.098	0.648	0.465	0.367	0.307	0.267	0.239	0.218	0.202	0.190	0.180	0.172	0.166	0.160	0.156	0.152	0.149	0.146	0.144	0.141
	A	6.3	10.7	15.0	19.1	23.0	26.7	30.2	33.4	36.4	39.2	41.8	44.2	46.5	48.5	50.4	52.2	53.8	55.3	56.7	58.0
	K	******	1.60	2.30	3.05	3.84	4.69	5.60	6.59	7.65	8.79	10.01	11.33	12.73	14.23	15.82	17.50	19.28	21.16	23.14	25.22

CARRIERS 12 PICKS 3 ENDS 7

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	92.1	62.0	45.9	36.7	30.9	27.0	24.1	22.1	20.5	19.2	18.2	17.4	16.8	16.2	15.8	15.4	15.1	14.8	14.6	14.4
	F	0.719	0.384	0.265	0.205	0.169	0.145	0.129	0.117	0.108	0.101	0.096	0.091	0.088	0.085	0.082	0.080	0.079	0.077	0.076	0.075
	A	5.0	9.5	13.8	17.9	21.9	25.7	29.2	32.5	35.6	38.5	41.1	43.6	45.9	48.0	49.9	51.7	53.4	54.9	56.3	57.7
	K	1.40	2.68	4.00	5.40	6.88	8.47	10.17	12.01	13.99	16.12	18.41	20.86	23.49	26.29	29.26	32.42	35.76	39.29	43.00	46.91
0.004	%C	99.4	75.2	57.6	46.8	39.7	34.9	31.3	28.7	26.7	25.1	23.9	22.8	22.0	21.3	20.7	20.2	19.8	19.5	19.2	18.9
	F	0.926	0.502	0.349	0.270	0.224	0.193	0.171	0.156	0.144	0.135	0.127	0.122	0.117	0.113	0.110	0.107	0.105	0.103	0.101	0.099
	A	5.2	9.6	13.9	18.1	22.1	25.8	29.4	32.7	35.7	38.6	41.2	43.7	45.9	48.0	50.0	51.8	53.4	55.0	56.4	57.7
	K	1.09	2.05	3.04	4.09	5.21	6.40	7.68	9.06	10.55	12.15	13.88	15.72	17.70	19.80	22.04	24.41	26.93	29.58	32.37	35.30
0.005	%C******		85.3	67.6	55.8	47.8	42.2	38.1	35.0	32.6	30.8	29.3	28.1	27.0	26.2	25.5	24.9	24.4	24.0	23.6	23.3
	F	1.119	0.617	0.431	0.335	0.278	0.240	0.213	0.194	0.179	0.168	0.159	0.152	0.146	0.141	0.137	0.134	0.131	0.128	0.126	0.124
	A	5.4	9.8	14.1	18.3	22.2	26.0	29.5	32.8	35.9	38.7	41.3	43.8	46.0	48.1	50.0	51.8	53.5	55.0	56.4	57.8
	K******		1.67	2.47	3.31	4.20	5.16	6.19	7.30	8.49	9.78	11.16	12.64	14.22	15.91	17.71	19.61	21.62	23.75	25.99	28.34
0.006	%C******		92.6	76.1	63.9	55.3	49.1	44.5	41.0	38.3	36.2	34.5	33.1	31.9	30.9	30.1	29.5	28.9	28.4	27.9	27.6
	F	1.300	0.727	0.511	0.399	0.331	0.286	0.255	0.232	0.215	0.201	0.190	0.182	0.175	0.169	0.164	0.160	0.157	0.154	0.151	0.149
	A	5.6	10.0	14.3	18.4	22.4	26.1	29.6	32.9	36.0	38.8	41.4	43.9	46.1	48.2	50.1	51.9	53.6	55.1	56.5	57.8
	K******		1.42	2.08	2.79	3.53	4.33	5.19	6.12	7.12	8.19	9.35	10.58	11.91	13.32	14.82	16.41	18.09	19.86	21.73	23.69
0.007	%C******		97.2	83.1	71.0	62.0	55.4	50.5	46.7	43.7	41.3	39.4	37.9	36.6	35.5	34.6	33.8	33.2	32.6	32.1	31.7
	F	1.470	0.834	0.589	0.461	0.384	0.332	0.296	0.270	0.250	0.234	0.222	0.212	0.204	0.197	0.191	0.187	0.183	0.179	0.176	0.174
	A	5.7	10.2	14.4	18.6	22.5	26.3	29.8	33.0	36.1	38.9	41.5	44.0	46.2	48.3	50.2	52.0	53.6	55.1	56.6	57.9
	K******		1.24	1.81	2.41	3.05	3.74	4.48	5.28	6.14	7.06	8.05	9.12	10.25	11.46	12.75	14.12	15.56	17.09	18.69	20.38
0.008	%C******		99.6	88.8	77.2	68.2	61.3	56.1	52.0	48.8	46.2	44.2	42.5	41.1	39.9	38.9	38.1	37.4	36.7	36.2	35.7
	F	1.629	0.937	0.666	0.523	0.436	0.378	0.337	0.307	0.284	0.267	0.253	0.242	0.232	0.225	0.218	0.213	0.209	0.205	0.201	0.198
	A	5.9	10.3	14.6	18.7	22.7	26.4	29.9	33.2	36.2	39.0	41.6	44.1	46.3	48.4	50.3	52.0	53.7	55.2	56.6	57.9
	K******		1.10	1.60	2.13	2.70	3.30	3.95	4.65	5.40	6.21	7.08	8.01	9.01	10.08	11.21	12.40	13.67	15.01	16.41	17.89
0.010	%C*************			96.5	87.3	78.6	71.7	66.1	61.7	58.2	55.4	53.1	51.1	49.5	48.2	47.1	46.1	45.3	44.6	43.9	43.4
	F	1.921	1.134	0.814	0.643	0.538	0.468	0.418	0.381	0.354	0.332	0.315	0.301	0.290	0.280	0.272	0.266	0.260	0.255	0.251	0.248
	A	6.3	10.7	15.0	19.1	23.0	26.7	30.2	33.4	36.4	39.2	41.8	44.2	46.5	48.5	50.4	52.2	53.8	55.3	56.7	58.0
	K*************			1.32	1.74	2.19	2.68	3.20	3.76	4.37	5.02	5.72	6.47	7.28	8.13	9.04	10.00	11.02	12.09	13.22	14.41

		CARRIERS 12	PICKS 3	ENDS 10

TR.DIA. — DIAMETER OVER DIELECTRIC

TR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	79.6	61.3	49.9	42.4	37.2	33.5	30.7	28.5	26.8	25.5	24.4	23.5	22.8	22.1	21.6	21.2	20.8	20.5	20.2
	F	1.027	0.548	0.378	0.292	0.241	0.208	0.184	0.167	0.155	0.145	0.137	0.131	0.125	0.121	0.118	0.115	0.112	0.110	0.108	0.107
	A	5.0	9.5	13.8	17.9	21.9	25.7	29.2	32.5	35.6	38.5	41.1	43.6	45.9	48.0	49.9	51.7	53.4	54.9	56.3	57.7
	K	******	1.88	2.80	3.78	4.82	5.93	7.12	8.40	9.79	11.28	12.88	14.60	16.44	18.40	20.48	22.70	25.03	27.50	30.10	32.83
0.004	%C	******	92.0	74.8	62.3	53.7	47.5	43.0	39.5	36.9	34.8	33.1	31.7	30.6	29.7	28.9	28.2	27.7	27.2	26.7	26.4
	F	1.323	0.717	0.498	0.386	0.319	0.276	0.245	0.222	0.205	0.192	0.182	0.174	0.167	0.161	0.157	0.153	0.149	0.147	0.144	0.142
	A	5.2	9.6	13.9	18.1	22.1	25.8	29.4	32.7	35.7	38.6	41.2	43.7	45.9	48.0	50.0	51.8	53.4	55.0	56.4	57.7
	K	******	1.43	2.13	2.86	3.64	4.48	5.38	6.34	7.39	8.51	9.71	11.01	12.39	13.86	15.43	17.09	18.85	20.70	22.66	24.71
0.005	%C	******	98.6	85.2	72.8	63.6	56.8	51.7	47.7	44.7	42.2	40.3	38.7	37.3	36.2	35.3	34.5	33.8	33.3	32.8	32.3
	F	1.599	0.881	0.615	0.479	0.397	0.343	0.305	0.277	0.256	0.240	0.227	0.217	0.208	0.201	0.196	0.191	0.187	0.183	0.180	0.177
	A	5.4	9.8	14.1	18.3	22.2	26.0	29.5	32.8	35.9	38.7	41.3	43.8	46.0	48.1	50.0	51.8	53.5	55.0	56.4	57.8
	K	******	1.17	1.73	2.32	2.94	3.61	4.33	5.11	5.94	6.84	7.81	8.85	9.96	11.14	12.39	13.73	15.14	16.62	18.19	19.84
0.006	%C	******	******	92.7	81.5	72.2	65.1	59.6	55.3	51.9	49.2	47.0	45.2	43.7	42.5	41.4	40.5	39.7	39.1	38.5	38.0
	F	1.857	1.039	0.730	0.570	0.473	0.409	0.364	0.331	0.306	0.287	0.272	0.260	0.250	0.241	0.235	0.229	0.224	0.220	0.216	0.213
	A	5.6	10.0	14.3	18.4	22.4	26.1	29.6	32.9	36.0	38.8	41.4	43.9	46.1	48.2	50.1	51.9	53.6	55.1	56.5	57.8
	K	******	******	1.46	1.95	2.47	3.03	3.63	4.28	4.98	5.73	6.54	7.41	8.33	9.32	10.37	11.48	12.66	13.90	15.21	16.59
0.007	%C	******	******	97.5	88.4	79.6	72.4	66.7	62.2	58.6	55.7	53.3	51.4	49.7	48.4	47.2	46.2	45.4	44.6	44.0	43.4
	F	2.099	1.191	0.842	0.659	0.548	0.475	0.423	0.385	0.357	0.334	0.317	0.303	0.291	0.281	0.273	0.267	0.261	0.256	0.252	0.248
	A	5.7	10.2	14.4	18.6	22.5	26.3	29.8	33.0	36.1	38.9	41.5	44.0	46.2	48.3	50.2	52.0	53.6	55.1	56.6	57.9
	K	******	******	1.27	1.69	2.14	2.62	3.14	3.69	4.29	4.94	5.64	6.38	7.18	8.03	8.93	9.88	10.89	11.96	13.08	14.26
0.008	%C	******	******	99.8	93.6	85.8	78.8	73.1	68.5	64.8	61.7	59.2	57.1	55.4	53.9	52.7	51.6	50.7	49.9	49.2	48.6
	F	2.327	1.339	0.951	0.747	0.623	0.540	0.482	0.439	0.406	0.381	0.361	0.345	0.332	0.321	0.312	0.304	0.298	0.292	0.287	0.283
	A	5.9	10.3	14.6	18.7	22.7	26.4	29.9	33.2	36.2	39.0	41.6	44.1	46.3	48.4	50.3	52.0	53.7	55.2	56.6	57.9
	K	******	******	1.12	1.49	1.89	2.31	2.76	3.25	3.78	4.35	4.96	5.61	6.31	7.05	7.84	8.68	9.57	10.50	11.49	12.52
0.010	%C	******	******	******	99.3	94.6	89.0	83.8	79.3	75.5	72.4	69.7	67.5	65.6	64.1	62.7	61.5	60.5	59.7	58.9	58.2
	F	2.745	1.620	1.163	0.918	0.768	0.668	0.597	0.545	0.505	0.474	0.450	0.430	0.414	0.400	0.389	0.380	0.372	0.365	0.359	0.354
	A	6.3	10.7	15.0	19.1	23.0	26.7	30.2	33.4	36.4	39.2	41.8	44.2	46.5	48.5	50.4	52.2	53.8	55.3	56.7	58.0
	K	******	******	******	1.22	1.54	1.88	2.24	2.63	3.06	3.52	4.01	4.53	5.09	5.69	6.33	7.00	7.71	8.47	9.26	10.09

CARRIERS 12 PICKS 9 ENDS 4

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	66.7	42.5	33.1	28.6	26.1	24.6	23.6	22.9	22.4	22.1	21.8	21.6	21.4	21.3	21.2	21.1	21.0	21.0	20.9	20.9
	F	0.423	0.242	0.182	0.155	0.140	0.131	0.126	0.122	0.119	0.117	0.116	0.114	0.114	0.113	0.112	0.112	0.111	0.111	0.111	0.110
	A	14.8	26.5	36.3	44.1	50.3	55.3	59.2	62.4	65.0	67.2	69.1	70.7	72.1	73.3	74.3	75.2	76.1	76.8	77.5	78.1
	K	2.53	5.17	8.45	12.53	17.50	23.43	30.34	38.24	47.16	57.09	68.04	80.01	93.00	107.02	122.06	138.13	155.22	173.35	192.49	212.67
0.004	%C	79.4	53.4	42.4	36.9	33.8	31.9	30.7	29.8	29.2	28.8	28.4	28.2	28.0	27.8	27.7	27.6	27.5	27.4	27.3	27.3
	F	0.546	0.317	0.241	0.206	0.186	0.175	0.167	0.162	0.159	0.156	0.154	0.153	0.151	0.150	0.150	0.149	0.148	0.148	0.147	0.147
	A	15.3	27.0	36.7	44.4	50.6	55.4	59.3	62.5	65.1	67.3	69.2	70.8	72.1	73.3	74.4	75.3	76.1	76.8	77.5	78.1
	K	1.97	3.97	6.45	9.53	13.29	17.77	22.98	28.94	35.65	43.13	51.37	60.38	70.15	80.70	92.01	104.09	116.95	130.57	144.96	160.12
0.005	%C	88.5	62.9	50.9	44.6	41.1	38.9	37.4	36.4	35.7	35.2	34.8	34.5	34.2	34.0	33.9	33.8	33.6	33.5	33.5	33.4
	F	0.662	0.391	0.299	0.256	0.232	0.218	0.209	0.203	0.198	0.195	0.192	0.191	0.189	0.188	0.187	0.186	0.185	0.185	0.184	0.184
	A	15.8	27.4	37.0	44.7	50.8	55.6	59.5	62.6	65.2	67.4	69.2	70.8	72.2	73.4	74.4	75.3	76.1	76.9	77.5	78.1
	K	1.63	3.24	5.25	7.73	10.76	14.37	18.56	23.35	28.75	34.76	41.37	48.60	56.45	64.91	73.98	83.67	93.98	104.90	116.44	128.60
0.006	%C	94.7	71.1	58.5	51.8	47.9	45.4	43.8	42.7	41.9	41.3	40.8	40.5	40.2	40.0	39.8	39.7	39.5	39.4	39.3	39.3
	F	0.770	0.463	0.356	0.306	0.278	0.261	0.250	0.243	0.238	0.234	0.231	0.229	0.227	0.225	0.224	0.223	0.222	0.222	0.221	0.221
	A	16.3	27.8	37.4	45.0	51.0	55.8	59.6	62.7	65.3	67.5	69.3	70.9	72.2	73.4	74.4	75.4	76.2	76.9	77.6	78.2
	K	1.41	2.76	4.45	6.54	9.08	12.10	15.62	19.63	24.15	29.17	34.71	40.76	47.31	54.38	61.97	70.06	78.67	87.79	97.43	107.58
0.007	%C	98.4	78.1	65.4	58.4	54.2	51.6	49.8	48.6	47.7	47.1	46.6	46.2	45.9	45.7	45.5	45.3	45.2	45.0	44.9	44.9
	F	0.873	0.532	0.412	0.355	0.323	0.304	0.292	0.283	0.277	0.273	0.269	0.267	0.265	0.263	0.262	0.260	0.259	0.259	0.258	0.257
	A	16.8	28.2	37.7	45.2	51.2	55.9	59.8	62.9	65.4	67.6	69.4	70.9	72.3	73.4	74.5	75.4	76.2	76.9	77.6	78.2
	K	1.25	2.42	3.88	5.68	7.88	10.49	13.52	16.97	20.86	25.19	29.95	35.15	40.79	46.87	53.38	60.34	67.74	75.57	83.85	92.57
0.008	%C	99.9	84.0	71.6	64.4	60.1	57.3	55.5	54.2	53.3	52.6	52.1	51.6	51.3	51.1	50.8	50.7	50.5	50.4	50.3	50.2
	F	0.970	0.600	0.467	0.404	0.368	0.347	0.333	0.323	0.316	0.311	0.308	0.305	0.302	0.300	0.299	0.298	0.297	0.296	0.295	0.294
	A	17.3	28.7	38.0	45.5	51.4	56.1	59.9	63.0	65.5	67.6	69.4	71.0	72.3	73.5	74.5	75.4	76.2	77.0	77.6	78.2
	K	1.13	2.16	3.45	5.04	6.98	9.27	11.94	14.98	18.40	22.20	26.38	30.95	35.90	41.23	46.95	53.05	59.54	66.41	73.67	81.31
0.010	%C	******	92.8	82.0	75.0	70.6	67.7	65.8	64.4	63.4	62.6	62.1	61.6	61.3	61.0	60.7	60.5	60.4	60.2	60.1	60.0
	F	1.149	0.731	0.576	0.500	0.458	0.432	0.415	0.403	0.395	0.389	0.384	0.381	0.378	0.375	0.373	0.372	0.371	0.369	0.369	0.368
	A	18.3	29.5	38.7	46.0	51.8	56.4	60.2	63.2	65.7	67.8	69.6	71.1	72.4	73.6	74.6	75.5	76.3	77.0	77.7	78.2
	K	******	1.80	2.85	4.15	5.72	7.58	9.73	12.19	14.95	18.02	21.39	25.06	29.05	33.34	37.94	42.84	48.06	53.58	59.41	65.55

				CARRIERS 12	PICKS 9	ENDS 7															
STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	93.3	66.7	53.6	46.9	43.1	40.7	39.2	38.1	37.3	36.8	36.4	36.0	35.8	35.6	35.4	35.3	35.2	35.1	35.0	34.9
	F	0.741	0.423	0.319	0.271	0.245	0.230	0.220	0.213	0.208	0.205	0.202	0.200	0.199	0.197	0.196	0.195	0.195	0.194	0.194	0.193
	A	14.8	26.5	36.3	44.1	50.3	55.3	59.2	62.4	65.0	67.2	69.1	70.7	72.1	73.3	74.3	75.2	76.1	76.8	77.5	78.1
	K	1.44	2.95	4.83	7.16	10.00	13.39	17.34	21.85	26.95	32.62	38.88	45.72	53.14	61.15	69.75	78.93	88.70	99.05	110.00	121.53
0.004	%C	99.8	80.2	66.6	59.0	54.6	51.8	50.0	48.7	47.8	47.2	46.7	46.3	45.9	45.7	45.5	45.3	45.2	45.1	45.0	44.9
	F	0.956	0.556	0.422	0.360	0.326	0.306	0.293	0.284	0.278	0.273	0.270	0.267	0.265	0.263	0.262	0.261	0.260	0.259	0.258	0.258
	A	15.3	27.0	36.7	44.4	50.6	55.4	59.3	62.5	65.1	67.3	69.2	70.8	72.1	73.3	74.4	75.3	76.1	76.8	77.5	78.1
	K	1.12	2.27	3.68	5.45	7.59	10.15	13.13	16.53	20.37	24.65	29.36	34.50	40.09	46.11	52.58	59.48	66.83	74.61	82.84	91.50
0.005	%C	******	90.0	77.3	69.5	64.8	61.8	59.8	58.4	57.3	56.6	56.0	55.6	55.2	54.9	54.7	54.5	54.4	54.2	54.1	54.0
	F	1.158	0.684	0.523	0.448	0.407	0.382	0.366	0.355	0.347	0.341	0.337	0.334	0.331	0.329	0.327	0.326	0.324	0.323	0.323	0.322
	A	15.8	27.4	37.0	44.7	50.8	55.6	59.5	62.6	65.2	67.4	69.2	70.8	72.2	73.4	74.4	75.3	76.1	76.9	77.5	78.1
	K	******	1.85	3.00	4.42	6.15	8.21	10.61	13.34	16.43	19.86	23.64	27.77	32.26	37.09	42.28	47.81	53.70	59.94	66.54	73.48
0.006	%C	******	96.4	85.8	78.4	73.6	70.5	68.4	67.0	65.9	65.1	64.5	64.0	63.6	63.3	63.1	62.9	62.7	62.6	62.4	62.3
	F	1.348	0.810	0.623	0.535	0.486	0.457	0.438	0.425	0.416	0.409	0.404	0.400	0.397	0.394	0.392	0.391	0.389	0.388	0.387	0.386
	A	16.3	27.8	37.4	45.0	51.0	55.8	59.6	62.7	65.3	67.5	69.3	70.9	72.2	73.4	74.4	75.4	76.2	76.9	77.6	78.2
	K	******	1.58	2.54	3.74	5.19	6.92	8.92	11.22	13.80	16.67	19.83	23.29	27.04	31.08	35.41	40.04	44.96	50.17	55.67	61.47
0.007	%C	******	99.5	92.2	85.6	81.1	78.1	76.0	74.6	73.5	72.7	72.0	71.5	71.2	70.8	70.6	70.4	70.2	70.0	69.9	69.8
	F	1.527	0.932	0.721	0.621	0.566	0.532	0.510	0.496	0.485	0.477	0.471	0.467	0.463	0.460	0.458	0.456	0.454	0.453	0.452	0.451
	A	16.8	28.2	37.7	45.2	51.2	55.9	59.8	62.9	65.4	67.6	69.4	70.9	72.3	73.4	74.5	75.4	76.2	76.9	77.6	78.2
	K	******	1.38	2.21	3.25	4.50	5.99	7.72	9.70	11.92	14.39	17.11	20.09	23.31	26.78	30.50	34.48	38.71	43.19	47.92	52.90
0.008	%C	************		96.7	91.4	87.4	84.6	82.6	81.1	80.1	79.3	78.7	78.2	77.8	77.5	77.2	77.0	76.9	76.7	76.6	76.5
	F	1.697	1.051	0.818	0.707	0.645	0.607	0.583	0.566	0.554	0.545	0.538	0.533	0.529	0.526	0.523	0.521	0.519	0.517	0.516	0.515
	A	17.3	28.7	38.0	45.5	51.4	56.1	59.9	63.0	65.5	67.6	69.4	71.0	72.3	73.5	74.5	75.4	76.2	77.0	77.6	78.2
	K	************		1.97	2.88	3.99	5.30	6.82	8.56	10.51	12.68	15.07	17.68	20.51	23.56	26.83	30.31	34.02	37.95	42.10	46.46
0.010	%C	******************			98.4	96.1	94.0	92.5	91.3	90.5	89.8	89.3	88.8	88.5	88.2	88.0	87.8	87.6	87.5	87.4	87.3
	F	2.011	1.280	1.008	0.875	0.801	0.756	0.726	0.706	0.691	0.680	0.672	0.666	0.661	0.657	0.653	0.651	0.648	0.647	0.645	0.643
	A	18.3	29.5	38.7	46.0	51.8	56.4	60.2	63.2	65.7	67.8	69.6	71.1	72.4	73.6	74.6	75.5	76.3	77.0	77.7	78.2
	K	******************			2.37	3.27	4.33	5.56	6.97	8.54	10.29	12.22	14.32	16.60	19.05	21.68	24.48	27.46	30.62	33.95	37.46

	CARRIERS	PICKS	ENDS
	12	9	10

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	84.3	70.4	62.5	57.8	54.9	53.0	51.6	50.7	50.0	49.4	49.0	48.7	48.4	48.2	48.0	47.9	47.8	47.7	47.6
	F	1.058	0.604	0.456	0.388	0.351	0.329	0.314	0.305	0.298	0.293	0.289	0.286	0.284	0.282	0.280	0.279	0.278	0.277	0.277	0.276
	A	14.8	26.5	36.3	44.1	50.3	55.3	59.2	62.4	65.0	67.2	69.1	70.7	72.1	73.3	74.3	75.2	76.1	76.8	77.5	78.1
	K	******	2.07	3.38	5.01	7.00	9.37	12.13	15.30	18.86	22.84	27.21	32.00	37.20	42.81	48.82	55.25	62.09	69.34	77.00	85.07
0.004	%C	******	95.7	84.2	76.4	71.5	68.3	66.2	64.7	63.6	62.8	62.2	61.7	61.3	61.0	60.8	60.6	60.4	60.3	60.1	60.0
	F	1.365	0.794	0.603	0.514	0.466	0.437	0.418	0.406	0.397	0.390	0.385	0.381	0.378	0.376	0.374	0.372	0.371	0.370	0.369	0.368
	A	15.3	27.0	36.7	44.4	50.6	55.4	59.3	62.5	65.1	67.3	69.2	70.8	72.1	73.3	74.4	75.3	76.1	76.8	77.5	78.1
	K	******	1.59	2.58	3.81	5.32	7.11	9.19	11.57	14.26	17.25	20.55	24.15	28.06	32.28	36.80	41.64	46.78	52.23	57.98	64.05
0.005	%C	******	100.0	93.6	87.0	82.4	79.3	77.2	75.7	74.6	73.7	73.1	72.6	72.2	71.9	71.6	71.4	71.2	71.1	70.9	70.8
	F	1.654	0.978	0.747	0.640	0.581	0.545	0.522	0.507	0.496	0.487	0.481	0.476	0.473	0.470	0.467	0.465	0.463	0.462	0.461	0.460
	A	15.8	27.4	37.0	44.7	50.8	55.6	59.5	62.6	65.2	67.4	69.2	70.8	72.2	73.4	74.4	75.3	76.1	76.9	77.5	78.1
	K	******	1.30	2.10	3.09	4.31	5.75	7.42	9.34	11.50	13.90	16.55	19.44	22.58	25.96	29.59	33.47	37.59	41.96	46.58	51.44
0.006	%C	******	******	98.8	94.4	90.7	88.0	86.0	84.6	83.5	82.7	82.1	81.6	81.3	80.9	80.7	80.5	80.3	80.1	80.0	79.9
	F	1.926	1.157	0.890	0.764	0.695	0.653	0.626	0.607	0.594	0.585	0.577	0.572	0.567	0.563	0.561	0.558	0.556	0.554	0.553	0.552
	A	16.3	27.8	37.4	45.0	51.0	55.8	59.6	62.7	65.3	67.5	69.3	70.9	72.2	73.4	74.4	75.4	76.2	76.9	77.6	78.2
	K	******	******	1.78	2.62	3.63	4.84	6.25	7.85	9.66	11.67	13.88	16.30	18.93	21.75	24.79	28.03	31.47	35.12	38.97	43.03
0.007	%C	******	******	******	98.7	96.3	94.3	92.7	91.5	90.6	89.9	89.3	88.9	88.5	88.3	88.0	87.8	87.7	87.5	87.4	87.3
	F	2.182	1.331	1.030	0.887	0.808	0.760	0.729	0.708	0.693	0.682	0.673	0.667	0.661	0.657	0.654	0.651	0.649	0.647	0.645	0.644
	A	16.8	28.2	37.7	45.2	51.2	55.9	59.8	62.9	65.4	67.6	69.4	70.9	72.3	73.4	74.5	75.4	76.2	76.9	77.6	78.2
	K	******	******	******	2.27	3.15	4.19	5.41	6.79	8.34	10.07	11.98	14.06	16.32	18.75	21.35	24.14	27.09	30.23	33.54	37.03
0.008	%C	******	******	******	******	99.4	98.2	97.2	96.3	95.6	95.1	94.7	94.3	94.0	93.8	93.6	93.4	93.3	93.2	93.1	93.0
	F	2.424	1.501	1.169	1.009	0.921	0.867	0.832	0.808	0.791	0.779	0.769	0.762	0.756	0.751	0.747	0.744	0.741	0.739	0.737	0.736
	A	17.3	28.7	38.0	45.5	51.4	56.1	59.9	63.0	65.5	67.6	69.4	71.0	72.3	73.5	74.5	75.4	76.2	77.0	77.6	78.2
	K	******	******	******	******	2.79	3.71	4.78	5.99	7.36	8.88	10.55	12.38	14.36	16.49	18.78	21.22	23.81	26.56	29.47	32.52
0.010	%C	******	******	******	******	******	******	******	******	100.0	99.9	99.8	99.8	99.7	99.6	99.6	99.5	99.5	99.4	99.4	99.3
	F	2.873	1.828	1.439	1.250	1.145	1.080	1.038	1.008	0.987	0.972	0.960	0.951	0.944	0.938	0.934	0.930	0.926	0.924	0.921	0.919
	A	18.3	29.5	38.7	46.0	51.8	56.4	60.2	63.2	65.7	67.8	69.6	71.1	72.4	73.6	74.6	75.5	76.3	77.0	77.7	78.2
	K	******	******	******	******	******	******	******	******	5.98	7.21	8.55	10.02	11.62	13.33	15.17	17.14	19.22	21.43	23.76	26.22

CARRIERS 12 PICKS 15 ENDS 4

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	69.4	48.4	41.1	37.8	36.2	35.2	34.6	34.2	33.9	33.7	33.5	33.4	33.3	33.2	33.2	33.1	33.1	33.0	33.0	33.0
	F	0.447	0.281	0.232	0.212	0.201	0.195	0.191	0.189	0.187	0.186	0.185	0.184	0.183	0.183	0.183	0.182	0.182	0.182	0.182	0.181
	A	23.7	39.8	50.8	58.3	63.6	67.4	70.3	72.6	74.4	75.9	77.1	78.1	79.0	79.8	80.4	81.0	81.5	82.0	82.4	82.8
	K	2.67	6.02	10.76	17.10	25.08	34.76	46.13	59.20	73.98	90.48	108.68	128.60	150.23	173.57	198.62	225.39	253.87	284.06	315.97	349.59
0.004	%C	82.3	60.4	52.1	48.4	46.4	45.2	44.5	44.0	43.6	43.4	43.2	43.0	42.9	42.8	42.7	42.7	42.6	42.6	42.6	42.5
	F	0.579	0.371	0.308	0.281	0.268	0.260	0.255	0.251	0.249	0.247	0.246	0.245	0.244	0.244	0.243	0.243	0.243	0.242	0.242	0.242
	A	24.5	40.3	51.1	58.5	63.7	67.5	70.4	72.7	74.5	75.9	77.1	78.2	79.0	79.8	80.5	81.0	81.6	82.0	82.4	82.8
	K	2.09	4.63	8.24	13.04	19.08	26.38	34.96	44.82	55.96	68.38	82.08	97.07	113.35	130.90	149.74	169.87	191.28	213.98	237.96	263.22
0.005	%C	91.2	70.7	62.0	57.9	55.6	54.3	53.5	53.0	52.6	52.3	52.1	51.9	51.8	51.7	51.6	51.5	51.5	51.4	51.4	51.3
	F	0.704	0.459	0.383	0.351	0.334	0.324	0.318	0.314	0.311	0.309	0.308	0.306	0.306	0.305	0.304	0.304	0.303	0.303	0.303	0.302
	A	25.2	40.8	51.5	58.8	63.9	67.7	70.5	72.7	74.5	76.0	77.2	78.2	79.1	79.8	80.5	81.1	81.6	82.0	82.4	82.8
	K	1.74	3.81	6.73	10.60	15.48	21.36	28.27	36.19	45.14	55.12	66.13	78.16	91.22	105.30	120.42	136.56	153.73	171.93	191.16	211.41
0.006	%C	96.8	79.3	70.6	66.4	64.0	62.6	61.8	61.2	60.7	60.4	60.2	60.0	59.9	59.8	59.7	59.6	59.5	59.5	59.4	59.4
	F	0.822	0.545	0.458	0.420	0.400	0.389	0.382	0.377	0.373	0.371	0.369	0.368	0.367	0.366	0.365	0.364	0.364	0.363	0.363	0.363
	A	26.0	41.3	51.8	59.0	64.1	67.8	70.6	72.8	74.6	76.0	77.2	78.2	79.1	79.9	80.5	81.1	81.6	82.1	82.5	82.8
	K	1.50	3.25	5.72	8.98	13.08	18.02	23.80	30.44	37.94	46.29	55.49	65.55	76.47	88.24	100.87	114.36	128.70	143.90	159.96	176.87
0.007	%C	99.6	86.3	78.1	73.9	71.5	70.1	69.2	68.6	68.1	67.8	67.6	67.4	67.2	67.1	67.0	66.9	66.9	66.8	66.8	66.7
	F	0.935	0.630	0.532	0.489	0.466	0.453	0.445	0.439	0.436	0.433	0.431	0.429	0.428	0.427	0.426	0.425	0.425	0.424	0.424	0.423
	A	26.7	41.8	52.2	59.2	64.3	67.9	70.7	72.9	74.7	76.1	77.3	78.3	79.1	79.9	80.5	81.1	81.6	82.1	82.5	82.8
	K	1.34	2.86	5.00	7.83	11.36	15.63	20.62	26.34	32.79	39.97	47.89	56.55	65.93	76.05	86.91	98.50	110.82	123.88	137.67	152.20
0.008	%C	******	91.7	84.4	80.4	78.1	76.7	75.8	75.2	74.8	74.4	74.2	74.0	73.9	73.7	73.6	73.6	73.5	73.4	73.4	73.3
	F	1.043	0.713	0.605	0.557	0.532	0.517	0.508	0.502	0.498	0.494	0.492	0.490	0.489	0.488	0.487	0.486	0.485	0.485	0.484	0.484
	A	27.4	42.3	52.5	59.5	64.4	68.1	70.8	73.0	74.7	76.1	77.3	78.3	79.2	79.9	80.6	81.1	81.6	82.1	82.5	82.9
	K	******	2.57	4.46	6.96	10.08	13.84	18.23	23.26	28.93	35.24	42.20	49.79	58.03	66.92	76.44	86.60	97.41	108.86	120.96	133.69
0.010	%C	******	98.4	93.7	90.6	88.7	87.5	86.6	86.1	85.7	85.4	85.2	85.0	84.8	84.7	84.6	84.6	84.5	84.5	84.4	84.4
	F	1.245	0.875	0.750	0.693	0.663	0.646	0.635	0.627	0.622	0.618	0.615	0.613	0.611	0.609	0.608	0.607	0.606	0.606	0.605	0.605
	A	28.8	43.3	53.2	59.9	64.8	68.3	71.0	73.1	74.8	76.2	77.4	78.4	79.2	80.0	80.6	81.2	81.7	82.1	82.5	82.9
	K	******	2.16	3.71	5.75	8.29	11.33	14.88	18.95	23.53	28.62	34.23	40.34	46.98	54.12	61.78	69.96	78.64	87.85	97.56	107.79

	CARRIERS 12	PICKS 15	ENDS 7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	95.3	74.2	64.8	60.3	58.0	56.6	55.7	55.1	54.7	54.4	54.2	54.0	53.9	53.8	53.7	53.6	53.6	53.5	53.5	53.4
	F	0.782	0.492	0.407	0.370	0.352	0.341	0.335	0.330	0.327	0.325	0.323	0.322	0.321	0.320	0.319	0.319	0.318	0.318	0.318	0.318
	A	23.7	39.8	50.8	58.3	63.6	67.4	70.3	72.6	74.4	75.9	77.1	78.1	79.0	79.8	80.4	81.0	81.5	82.0	82.4	82.8
	K	1.53	3.44	6.15	9.77	14.33	19.86	26.36	33.83	42.28	51.70	62.10	73.48	85.84	99.18	113.50	128.79	145.07	162.32	180.55	199.76
0.004	%C	******	87.7	78.8	74.2	71.7	70.2	69.3	68.6	68.2	67.9	67.6	67.4	67.3	67.1	67.0	67.0	66.9	66.8	66.8	66.7
	F	1.013	0.649	0.539	0.492	0.468	0.454	0.446	0.440	0.436	0.433	0.431	0.429	0.428	0.427	0.426	0.425	0.425	0.424	0.424	0.423
	A	24.5	40.3	51.1	58.5	63.7	67.5	70.4	72.7	74.5	75.9	77.1	78.2	79.0	79.8	80.5	81.0	81.6	82.0	82.4	82.8
	K	******	2.65	4.71	7.45	10.90	15.08	19.98	25.61	31.98	39.07	46.91	55.47	64.77	74.80	85.57	97.07	109.30	122.27	135.98	150.41
0.005	%C	******	96.1	89.2	85.1	82.7	81.3	80.4	79.7	79.3	78.9	78.7	78.5	78.3	78.2	78.1	78.0	78.0	77.9	77.9	77.8
	F	1.232	0.803	0.671	0.614	0.585	0.568	0.557	0.550	0.545	0.541	0.538	0.536	0.535	0.533	0.532	0.531	0.531	0.530	0.530	0.529
	A	25.2	40.8	51.5	58.8	63.9	67.7	70.5	72.7	74.5	76.0	77.2	78.2	79.1	79.8	80.5	81.1	81.6	82.0	82.4	82.8
	K	******	2.17	3.84	6.06	8.84	12.21	16.15	20.68	25.80	31.50	37.79	44.66	52.12	60.17	68.81	78.04	87.85	98.25	109.23	120.81
0.006	%C	******	99.8	96.1	93.0	91.0	89.8	89.0	88.4	88.0	87.7	87.5	87.3	87.2	87.0	86.9	86.9	86.8	86.8	86.7	86.7
	F	1.439	0.954	0.801	0.735	0.700	0.680	0.668	0.659	0.653	0.649	0.646	0.643	0.642	0.640	0.639	0.638	0.637	0.636	0.635	0.635
	A	26.0	41.3	51.8	59.0	64.1	67.8	70.6	72.8	74.6	76.0	77.2	78.2	79.1	79.9	80.5	81.1	81.6	82.1	82.5	82.8
	K	******	1.86	3.27	5.13	7.47	10.29	13.60	17.40	21.68	26.45	31.71	37.46	43.70	50.42	57.64	65.35	73.54	82.23	91.40	101.07
0.007	%C	******	******	99.5	97.9	96.6	95.7	95.1	94.7	94.3	94.1	93.9	93.8	93.7	93.6	93.5	93.4	93.4	93.3	93.3	93.3
	F	1.637	1.102	0.931	0.855	0.816	0.793	0.779	0.769	0.762	0.757	0.753	0.751	0.748	0.747	0.745	0.744	0.743	0.742	0.741	0.741
	A	26.7	41.8	52.2	59.2	64.3	67.9	70.7	72.9	74.7	76.1	77.3	78.3	79.1	79.9	80.5	81.1	81.6	82.1	82.5	82.8
	K	******	******	2.86	4.47	6.49	8.93	11.78	15.05	18.74	22.84	27.37	32.31	37.68	43.46	49.66	56.28	63.33	70.79	78.67	86.97
0.008	%C	******	******	******	99.9	99.5	99.1	98.8	98.5	98.3	98.2	98.1	98.0	97.9	97.8	97.8	97.8	97.7	97.7	97.7	97.6
	F	1.825	1.247	1.059	0.975	0.931	0.906	0.889	0.878	0.871	0.865	0.861	0.858	0.855	0.853	0.852	0.850	0.849	0.848	0.847	0.847
	A	27.4	42.3	52.5	59.5	64.4	68.1	70.8	73.0	74.7	76.1	77.3	78.3	79.2	79.9	80.6	81.1	81.6	82.1	82.5	82.9
	K	******	******	******	3.98	5.76	7.91	10.42	13.29	16.53	20.14	24.11	28.45	33.16	38.24	43.68	49.49	55.66	62.21	69.12	76.40
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	2.179	1.531	1.312	1.213	1.161	1.130	1.110	1.097	1.088	1.081	1.076	1.072	1.069	1.066	1.064	1.063	1.061	1.060	1.059	1.058
	A	28.8	43.3	53.2	59.9	64.8	68.3	71.0	73.1	74.8	76.2	77.4	78.4	79.2	80.0	80.6	81.2	81.7	82.1	82.5	82.9
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

	CARRIERS 12	PICKS 15	ENDS 10

STR.DIA. — DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	91.2	82.4	77.8	75.3	73.7	72.7	72.1	71.6	71.3	71.0	70.8	70.7	70.5	70.4	70.4	70.3	70.2	70.2	70.1
	F	1.118	0.703	0.581	0.529	0.503	0.487	0.478	0.472	0.467	0.464	0.462	0.460	0.458	0.457	0.456	0.456	0.455	0.454	0.454	0.454
	A	23.7	39.8	50.8	58.3	63.6	67.4	70.3	72.6	74.4	75.9	77.1	78.1	79.0	79.8	80.4	81.0	81.5	82.0	82.4	82.8
	K	******	2.41	4.31	6.84	10.03	13.90	18.45	23.68	29.59	36.19	43.47	51.44	60.09	69.43	79.45	90.15	101.55	113.62	126.39	139.83
0.004	%C	******	99.5	94.7	91.2	89.0	87.7	86.8	86.2	85.8	85.5	85.2	85.0	84.9	84.8	84.7	84.6	84.5	84.5	84.4	84.4
	F	1.447	0.928	0.771	0.703	0.669	0.649	0.637	0.629	0.623	0.619	0.615	0.613	0.611	0.610	0.608	0.607	0.607	0.606	0.605	0.605
	A	24.5	40.3	51.1	58.5	63.7	67.5	70.4	72.7	74.5	75.9	77.1	78.2	79.0	79.8	80.5	81.0	81.6	82.0	82.4	82.8
	K	******	1.85	3.30	5.22	7.63	10.55	13.98	17.93	22.38	27.35	32.83	38.83	45.34	52.36	59.90	67.95	76.51	85.59	95.18	105.29
0.005	%C	******	******	99.8	98.5	97.3	96.4	95.8	95.4	95.1	94.8	94.7	94.5	94.4	94.3	94.3	94.2	94.2	94.1	94.1	94.0
	F	1.759	1.147	0.958	0.877	0.835	0.811	0.796	0.785	0.778	0.773	0.769	0.766	0.764	0.762	0.760	0.759	0.758	0.757	0.757	0.756
	A	25.2	40.8	51.5	58.8	63.9	67.7	70.5	72.7	74.5	76.0	77.2	78.2	79.1	79.8	80.5	81.1	81.6	82.0	82.4	82.8
	K	******	******	2.69	4.24	6.19	8.54	11.31	14.48	18.06	22.05	26.45	31.26	36.49	42.12	48.17	54.62	61.49	68.77	76.46	84.56
0.006	%C	******	******	******	******	******	99.9	99.8	99.7	99.6	99.5	99.4	99.3	99.3	99.3	99.2	99.2	99.2	99.2	99.2	99.1
	F	2.056	1.363	1.145	1.050	1.001	0.972	0.954	0.942	0.934	0.927	0.923	0.919	0.916	0.914	0.912	0.911	0.910	0.909	0.908	0.907
	A	26.0	41.3	51.8	59.0	64.1	67.8	70.6	72.8	74.6	76.0	77.2	78.2	79.1	79.9	80.5	81.1	81.6	82.1	82.5	82.8
	K	******	******	******	******	******	7.21	9.52	12.18	15.17	18.51	22.20	26.22	30.59	35.30	40.35	45.74	51.48	57.56	63.98	70.75
0.007	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	2.338	1.574	1.329	1.222	1.166	1.133	1.112	1.099	1.089	1.082	1.076	1.072	1.069	1.067	1.064	1.063	1.061	1.060	1.059	1.058
	A	26.7	41.8	52.2	59.2	64.3	67.9	70.7	72.9	74.7	76.1	77.3	78.3	79.1	79.9	80.5	81.1	81.6	82.1	82.5	82.8
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.008	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	2.608	1.782	1.512	1.393	1.330	1.294	1.271	1.255	1.244	1.236	1.230	1.225	1.222	1.219	1.216	1.215	1.213	1.212	1.210	1.209
	A	27.4	42.3	52.5	59.5	64.4	68.1	70.8	73.0	74.7	76.1	77.3	78.3	79.2	79.9	80.6	81.1	81.6	82.1	82.5	82.9
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	3.114	2.187	1.874	1.733	1.658	1.614	1.586	1.567	1.554	1.544	1.537	1.531	1.527	1.523	1.520	1.518	1.516	1.514	1.513	1.512
	A	28.8	43.3	53.2	59.9	64.8	68.3	71.0	73.1	74.8	76.2	77.4	78.4	79.2	80.0	80.6	81.2	81.7	82.1	82.5	82.9
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

CARRIERS	PICKS	ENDS
16	3	4

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	79.5	49.7	35.9	28.2	23.4	20.1	17.7	16.0	14.6	13.6	12.7	12.0	11.4	10.9	10.5	10.2	9.9	9.6	9.4	9.2
	F	0.547	0.291	0.199	0.153	0.125	0.106	0.093	0.083	0.076	0.070	0.066	0.062	0.059	0.056	0.054	0.052	0.051	0.049	0.048	0.047
	A	3.8	7.1	10.4	13.6	16.8	19.8	22.8	25.6	28.2	30.8	33.2	35.5	37.7	39.8	41.7	43.5	45.2	46.9	48.4	49.8
	K	1.84	3.50	5.19	6.94	8.75	10.64	12.63	14.73	16.94	19.28	21.75	24.37	27.13	30.05	33.13	36.37	39.78	43.36	47.12	51.05
0.004	%C	91.2	61.6	45.6	36.3	30.3	26.2	23.2	20.9	19.2	17.8	16.7	15.8	15.1	14.4	13.9	13.4	13.0	12.7	12.4	12.2
	F	0.704	0.380	0.262	0.202	0.165	0.141	0.124	0.111	0.101	0.093	0.087	0.082	0.078	0.075	0.072	0.070	0.068	0.066	0.064	0.063
	A	3.9	7.3	10.5	13.8	16.9	19.9	22.9	25.7	28.3	30.9	33.3	35.6	37.8	39.8	41.8	43.6	45.3	46.9	48.5	49.9
	K	1.43	2.67	3.94	5.26	6.62	8.04	9.54	11.11	12.77	14.53	16.39	18.36	20.43	22.63	24.94	27.38	29.94	32.63	35.46	38.41
0.005	%C	97.8	71.6	54.3	43.7	36.8	31.9	28.4	25.7	23.6	21.9	20.6	19.5	18.6	17.8	17.2	16.6	16.1	15.7	15.4	15.1
	F	0.851	0.467	0.324	0.250	0.205	0.175	0.154	0.138	0.126	0.117	0.109	0.103	0.098	0.094	0.090	0.087	0.084	0.082	0.080	0.078
	A	4.0	7.4	10.7	13.9	17.0	20.1	23.0	25.8	28.5	31.0	33.4	35.7	37.9	39.9	41.8	43.7	45.4	47.0	48.5	50.0
	K	1.18	2.18	3.20	4.25	5.34	6.48	7.68	8.94	10.27	11.68	13.17	14.75	16.42	18.17	20.03	21.98	24.04	26.20	28.46	30.82
0.006	%C	100.0	79.8	62.1	50.6	42.9	37.4	33.3	30.3	27.9	25.9	24.4	23.1	22.0	21.2	20.4	19.7	19.2	18.7	18.3	17.9
	F	0.988	0.550	0.384	0.297	0.244	0.209	0.184	0.165	0.151	0.139	0.130	0.123	0.117	0.112	0.108	0.104	0.101	0.098	0.096	0.094
	A	4.2	7.5	10.8	14.0	17.2	20.2	23.1	25.9	28.6	31.1	33.5	35.8	38.0	40.0	41.9	43.7	45.4	47.1	48.6	50.0
	K	1.02	1.85	2.70	3.58	4.49	5.44	6.44	7.49	8.61	9.78	11.03	12.35	13.74	15.21	16.76	18.39	20.10	21.90	23.79	25.77
0.007	%C	******	86.4	69.0	56.9	48.6	42.6	38.1	34.7	32.0	29.8	28.1	26.6	25.4	24.4	23.5	22.8	22.2	21.6	21.1	20.7
	F	1.117	0.631	0.443	0.344	0.283	0.242	0.213	0.192	0.175	0.162	0.152	0.143	0.136	0.130	0.126	0.121	0.118	0.115	0.112	0.110
	A	4.3	7.6	10.9	14.2	17.3	20.3	23.2	26.0	28.7	31.2	33.6	35.9	38.0	40.1	42.0	43.8	45.5	47.1	48.6	50.1
	K	******	1.61	2.34	3.10	3.88	4.70	5.55	6.46	7.42	8.43	9.50	10.63	11.82	13.09	14.42	15.82	17.29	18.84	20.46	22.16
0.008	%C	******	91.5	75.0	62.7	53.9	47.5	42.6	38.9	35.9	33.5	31.6	30.0	28.7	27.6	26.6	25.8	25.1	24.5	23.9	23.5
	F	1.238	0.709	0.500	0.389	0.321	0.275	0.242	0.218	0.199	0.185	0.173	0.163	0.156	0.149	0.143	0.139	0.134	0.131	0.128	0.125
	A	4.4	7.8	11.1	14.3	17.4	20.4	23.3	26.1	28.8	31.3	33.7	36.0	38.1	40.1	42.1	43.9	45.6	47.2	48.7	50.1
	K	******	1.44	2.08	2.74	3.42	4.14	4.89	5.69	6.52	7.41	8.35	9.34	10.39	11.50	12.66	13.89	15.18	16.54	17.96	19.45
0.010	%C	******	98.0	84.9	72.8	63.5	56.5	51.0	46.8	43.4	40.7	38.4	36.6	35.0	33.7	32.5	31.6	30.7	30.0	29.3	28.8
	F	1.460	0.857	0.611	0.478	0.396	0.340	0.300	0.271	0.248	0.230	0.215	0.203	0.194	0.186	0.179	0.173	0.168	0.163	0.159	0.156
	A	4.7	8.0	11.3	14.5	17.6	20.7	23.6	26.3	29.0	31.5	33.9	36.1	38.3	40.3	42.2	44.0	45.7	47.3	48.8	50.2
	K	******	1.19	1.70	2.23	2.78	3.36	3.96	4.60	5.27	5.99	6.74	7.54	8.38	9.27	10.21	11.19	12.23	13.32	14.46	15.65

CARRIERS 16 PICKS 3 ENDS 7

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	99.8	75.8	57.6	46.3	38.9	33.7	29.9	27.1	24.9	23.1	21.7	20.5	19.5	18.7	18.0	17.5	17.0	16.5	16.1	15.8
	F	0.957	0.508	0.349	0.267	0.218	0.186	0.163	0.146	0.133	0.123	0.115	0.108	0.103	0.099	0.095	0.091	0.089	0.086	0.084	0.082
	A	3.8	7.1	10.4	13.6	16.8	19.8	22.8	25.6	28.2	30.8	33.2	35.5	37.7	39.8	41.7	43.5	45.2	46.9	48.4	49.8
	K	1.05	2.00	2.97	3.96	5.00	6.08	7.22	8.42	9.68	11.02	12.43	13.92	15.50	17.17	18.93	20.78	22.73	24.78	26.93	29.17
0.004	%C	******	88.8	70.7	58.1	49.4	43.2	38.6	35.0	32.3	30.0	28.2	26.8	25.5	24.5	23.6	22.9	22.2	21.7	21.2	20.8
	F	1.232	0.666	0.459	0.353	0.289	0.246	0.216	0.194	0.177	0.164	0.153	0.144	0.137	0.131	0.126	0.122	0.118	0.115	0.112	0.110
	A	3.9	7.3	10.5	13.8	16.9	19.9	22.9	25.7	28.3	30.9	33.3	35.6	37.8	39.8	41.8	43.6	45.3	46.9	48.5	49.9
	K	******	1.53	2.25	3.00	3.78	4.60	5.45	6.35	7.30	8.30	9.37	10.49	11.68	12.93	14.25	15.65	17.11	18.65	20.26	21.95
0.005	%C	******	96.7	81.2	68.3	58.8	51.8	46.6	42.5	39.2	36.6	34.5	32.7	31.3	30.1	29.0	28.1	27.3	26.7	26.1	25.6
	F	1.489	0.817	0.567	0.437	0.359	0.306	0.269	0.241	0.220	0.204	0.191	0.180	0.171	0.164	0.157	0.152	0.148	0.144	0.140	0.137
	A	4.0	7.4	10.7	13.9	17.0	20.1	23.0	25.8	28.5	31.0	33.4	35.7	37.9	39.9	41.8	43.7	45.4	47.0	48.5	50.0
	K	******	1.24	1.83	2.43	3.05	3.70	4.39	5.11	5.87	6.68	7.53	8.43	9.38	10.39	11.45	12.56	13.74	14.97	16.26	17.61
0.006	%C	******	99.9	89.2	77.0	67.2	59.7	53.9	49.4	45.8	42.8	40.4	38.4	36.8	35.4	34.2	33.1	32.2	31.5	30.8	30.2
	F	1.730	0.963	0.672	0.520	0.427	0.365	0.321	0.289	0.264	0.244	0.228	0.215	0.205	0.196	0.189	0.182	0.177	0.172	0.168	0.164
	A	4.2	7.5	10.8	14.0	17.2	20.2	23.1	25.9	28.6	31.1	33.5	35.8	38.0	40.0	41.9	43.7	45.4	47.1	48.6	50.0
	K	******	1.06	1.54	2.04	2.56	3.11	3.68	4.28	4.92	5.59	6.30	7.05	7.85	8.69	9.57	10.51	11.49	12.52	13.59	14.72
0.007	%C	******	******	94.9	84.1	74.5	66.8	60.7	55.8	51.9	48.7	46.1	43.9	42.0	40.5	39.1	38.0	37.0	36.1	35.3	34.7
	F	1.955	1.104	0.775	0.601	0.495	0.424	0.373	0.335	0.306	0.284	0.266	0.251	0.239	0.228	0.220	0.212	0.206	0.201	0.196	0.192
	A	4.3	7.6	10.9	14.2	17.3	20.3	23.2	26.0	28.7	31.2	33.6	35.9	38.0	40.1	42.0	43.8	45.5	47.1	48.6	50.1
	K	******	******	1.34	1.77	2.22	2.68	3.17	3.69	4.24	4.82	5.43	6.07	6.76	7.48	8.24	9.04	9.88	10.76	11.69	12.66
0.008	%C	******	******	98.4	89.8	80.8	73.1	66.9	61.8	57.6	54.2	51.4	49.0	47.0	45.3	43.9	42.6	41.5	40.6	39.7	39.0
	F	2.167	1.241	0.875	0.681	0.562	0.482	0.424	0.382	0.349	0.323	0.303	0.286	0.272	0.261	0.251	0.242	0.235	0.229	0.224	0.219
	A	4.4	7.8	11.1	14.3	17.4	20.4	23.3	26.1	28.8	31.3	33.7	36.0	38.1	40.1	42.1	43.9	45.6	47.2	48.7	50.1
	K	******	******	1.19	1.56	1.95	2.36	2.79	3.25	3.73	4.23	4.77	5.34	5.94	6.57	7.24	7.94	8.68	9.45	10.26	11.11
0.010	%C	******	******	******	97.3	90.6	83.6	77.5	72.3	67.9	64.2	61.1	58.5	56.3	54.4	52.7	51.3	50.1	49.0	48.0	47.2
	F	2.555	1.500	1.069	0.837	0.693	0.595	0.526	0.474	0.434	0.402	0.377	0.356	0.339	0.325	0.313	0.302	0.293	0.286	0.279	0.273
	A	4.7	8.0	11.3	14.5	17.6	20.7	23.6	26.3	29.0	31.5	33.9	36.1	38.3	40.3	42.2	44.0	45.7	47.3	48.8	50.2
	K	******	******	******	1.27	1.59	1.92	2.26	2.63	3.01	3.42	3.85	4.31	4.79	5.30	5.83	6.40	6.99	7.61	8.26	8.95

	CARRIERS 16	PICKS 3	ENDS 10

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	92.5	74.8	61.8	52.6	46.0	41.1	37.4	34.4	32.1	30.2	28.6	27.3	26.2	25.2	24.4	23.7	23.1	22.6	22.2
	F	1.367	0.726	0.498	0.382	0.312	0.265	0.233	0.209	0.190	0.176	0.164	0.155	0.147	0.141	0.135	0.131	0.127	0.123	0.120	0.118
	A	3.8	7.1	10.4	13.6	16.8	19.8	22.8	25.6	28.2	30.8	33.2	35.5	37.7	39.8	41.7	43.5	45.2	46.9	48.4	49.8
	K	******	1.40	2.08	2.77	3.50	4.26	5.05	5.89	6.78	7.71	8.70	9.75	10.85	12.02	13.25	14.55	15.91	17.35	18.85	20.42
0.004	%C	******	99.8	88.1	75.4	65.5	58.0	52.2	47.7	44.2	41.3	38.9	37.0	35.3	34.0	32.8	31.8	30.9	30.2	29.5	28.9
	F	1.760	0.951	0.656	0.504	0.413	0.352	0.309	0.277	0.253	0.234	0.218	0.206	0.196	0.187	0.180	0.174	0.169	0.164	0.160	0.157
	A	3.9	7.3	10.5	13.8	16.9	19.9	22.9	25.7	28.3	30.9	33.3	35.6	37.8	39.8	41.8	43.6	45.3	46.9	48.5	49.9
	K	******	1.07	1.58	2.10	2.65	3.22	3.81	4.44	5.11	5.81	6.56	7.34	8.17	9.05	9.98	10.95	11.98	13.05	14.18	15.36
0.005	%C	******	******	96.4	85.9	76.2	68.3	62.1	57.1	53.1	49.8	47.1	44.8	42.9	41.3	39.9	38.7	37.7	36.8	36.0	35.3
	F	2.127	1.167	0.810	0.625	0.512	0.437	0.384	0.345	0.315	0.291	0.272	0.257	0.244	0.234	0.225	0.217	0.211	0.205	0.200	0.196
	A	4.0	7.4	10.7	13.9	17.0	20.1	23.0	25.8	28.5	31.0	33.4	35.7	37.9	39.9	41.8	43.7	45.4	47.0	48.5	50.0
	K	******	******	1.28	1.70	2.14	2.59	3.07	3.58	4.11	4.67	5.27	5.90	6.57	7.27	8.01	8.79	9.62	10.48	11.38	12.33
0.006	%C	******	******	99.8	93.4	84.8	77.1	70.7	65.5	61.1	57.6	54.6	52.1	50.0	48.2	46.6	45.3	44.1	43.1	42.2	41.5
	F	2.471	1.376	0.960	0.743	0.610	0.522	0.459	0.412	0.377	0.348	0.326	0.308	0.293	0.280	0.269	0.260	0.253	0.246	0.240	0.235
	A	4.2	7.5	10.8	14.0	17.2	20.2	23.1	25.9	28.6	31.1	33.5	35.8	38.0	40.0	41.9	43.7	45.4	47.1	48.6	50.0
	K	******	******	1.08	1.43	1.79	2.18	2.58	3.00	3.44	3.91	4.41	4.94	5.49	6.08	6.70	7.35	8.04	8.76	9.52	10.31
0.007	%C	******	******	******	98.0	91.4	84.4	78.2	72.9	68.4	64.6	61.5	58.8	56.5	54.6	52.9	51.5	50.2	49.1	48.1	47.3
	F	2.793	1.578	1.107	0.859	0.707	0.605	0.533	0.479	0.438	0.405	0.379	0.358	0.341	0.326	0.314	0.303	0.294	0.287	0.280	0.274
	A	4.3	7.6	10.9	14.2	17.3	20.3	23.2	26.0	28.7	31.2	33.6	35.9	38.0	40.1	42.0	43.8	45.5	47.1	48.6	50.1
	K	******	******	******	1.24	1.55	1.88	2.22	2.58	2.97	3.37	3.80	4.25	4.73	5.23	5.77	6.33	6.92	7.53	8.18	8.86
0.008	%C	******	******	******	99.9	96.1	90.3	84.5	79.3	74.9	71.1	67.8	65.0	62.6	60.6	58.8	57.3	55.9	54.7	53.7	52.8
	F	3.096	1.773	1.250	0.973	0.803	0.688	0.606	0.545	0.499	0.462	0.433	0.409	0.389	0.372	0.358	0.346	0.336	0.327	0.319	0.313
	A	4.4	7.8	11.1	14.3	17.4	20.4	23.3	26.1	28.8	31.3	33.7	36.0	38.1	40.1	42.1	43.9	45.6	47.2	48.7	50.1
	K	******	******	******	1.09	1.37	1.66	1.96	2.27	2.61	2.96	3.34	3.74	4.16	4.60	5.06	5.56	6.07	6.62	7.18	7.78
0.010	%C	******	******	******	******	100.0	97.8	93.8	89.5	85.5	81.9	78.7	75.9	73.4	71.2	69.4	67.7	66.3	65.0	63.8	62.8
	F	3.650	2.143	1.528	1.196	0.990	0.850	0.751	0.676	0.619	0.574	0.538	0.509	0.484	0.464	0.447	0.432	0.419	0.408	0.399	0.390
	A	4.7	8.0	11.3	14.5	17.6	20.7	23.6	26.3	29.0	31.5	33.9	36.1	38.3	40.3	42.2	44.0	45.7	47.3	48.8	50.2
	K	******	******	******	******	1.11	1.34	1.59	1.84	2.11	2.39	2.70	3.02	3.35	3.71	4.08	4.48	4.89	5.33	5.78	6.26

CARRIERS 16 PICKS 9 ENDS 4

STR.DIA. DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	80.3	52.1	39.7	33.3	29.6	27.3	25.7	24.6	23.8	23.2	22.8	22.4	22.1	21.9	21.7	21.6	21.5	21.3	21.3	21.2
	F	0.556	0.308	0.224	0.183	0.161	0.147	0.138	0.132	0.127	0.124	0.121	0.119	0.118	0.116	0.115	0.114	0.114	0.113	0.113	0.112
	A	11.2	20.5	28.9	36.1	42.1	47.2	51.5	55.1	58.2	60.8	63.0	65.0	66.7	68.2	69.5	70.7	71.7	72.7	73.5	74.3
	K	1.87	3.70	5.83	8.34	11.30	14.75	18.72	23.24	28.30	33.93	40.12	46.88	54.20	62.11	70.58	79.63	89.26	99.46	110.24	121.59
0.004	%C	92.0	64.5	50.3	42.7	38.2	35.3	33.3	32.0	31.0	30.2	29.7	29.2	28.9	28.6	28.4	28.2	28.0	27.9	27.8	27.7
	F	0.717	0.404	0.295	0.243	0.214	0.196	0.184	0.175	0.169	0.165	0.161	0.159	0.157	0.155	0.154	0.153	0.152	0.151	0.150	0.150
	A	11.6	20.9	29.2	36.3	42.4	47.4	51.7	55.3	58.3	60.9	63.1	65.0	66.7	68.2	69.5	70.7	71.7	72.7	73.5	74.3
	K	1.45	2.84	4.44	6.34	8.57	11.17	14.17	17.57	21.39	25.62	30.28	35.37	40.88	46.83	53.20	60.00	67.24	74.91	83.01	91.54
0.005	%C	98.2	74.7	59.8	51.3	46.1	42.8	40.5	39.0	37.8	36.9	36.3	35.7	35.3	35.0	34.7	34.5	34.3	34.1	34.0	33.9
	F	0.868	0.497	0.366	0.302	0.266	0.244	0.229	0.219	0.211	0.206	0.202	0.198	0.196	0.194	0.192	0.191	0.189	0.189	0.188	0.187
	A	12.0	21.2	29.5	36.6	42.6	47.6	51.8	55.4	58.4	61.0	63.2	65.1	66.8	68.3	69.6	70.7	71.8	72.7	73.6	74.4
	K	1.20	2.32	3.61	5.13	6.93	9.03	11.44	14.17	17.24	20.64	24.38	28.46	32.89	37.66	42.77	48.23	54.03	60.18	66.67	73.52
0.006	%C	******	82.9	68.0	59.1	53.5	49.8	47.3	45.5	44.2	43.3	42.5	41.9	41.5	41.1	40.8	40.5	40.3	40.1	40.0	39.8
	F	1.009	0.587	0.435	0.360	0.318	0.292	0.274	0.262	0.253	0.247	0.242	0.238	0.235	0.232	0.230	0.229	0.227	0.226	0.225	0.224
	A	12.4	21.6	29.8	36.8	42.8	47.8	52.0	55.5	58.5	61.1	63.3	65.2	66.9	68.3	69.6	70.8	71.8	72.8	73.6	74.4
	K	******	1.97	3.05	4.33	5.84	7.60	9.62	11.91	14.47	17.32	20.45	23.86	27.56	31.55	35.82	40.38	45.23	50.36	55.78	61.50
0.007	%C	******	89.4	75.3	66.1	60.2	56.3	53.6	51.7	50.3	49.3	48.4	47.8	47.3	46.9	46.5	46.2	46.0	45.8	45.6	45.5
	F	1.142	0.674	0.503	0.418	0.369	0.339	0.319	0.305	0.295	0.288	0.282	0.277	0.274	0.271	0.269	0.267	0.265	0.264	0.263	0.262
	A	12.7	21.9	30.1	37.1	43.0	48.0	52.1	55.6	58.6	61.2	63.4	65.3	66.9	68.4	69.7	70.8	71.9	72.8	73.6	74.4
	K	******	1.72	2.66	3.76	5.06	6.58	8.32	10.29	12.50	14.95	17.64	20.58	23.76	27.18	30.85	34.77	38.94	43.35	48.01	52.91
0.008	%C	******	94.2	81.4	72.4	66.4	62.4	59.6	57.5	56.0	54.9	54.0	53.3	52.8	52.3	52.0	51.7	51.4	51.2	51.0	50.9
	F	1.268	0.759	0.569	0.475	0.420	0.387	0.364	0.348	0.337	0.328	0.322	0.317	0.313	0.310	0.307	0.305	0.303	0.301	0.300	0.299
	A	13.1	22.3	30.4	37.4	43.2	48.2	52.3	55.8	58.7	61.3	63.4	65.3	67.0	68.4	69.7	70.9	71.9	72.8	73.7	74.4
	K	******	1.54	2.36	3.33	4.48	5.81	7.34	9.08	11.02	13.17	15.53	18.11	20.90	23.91	27.13	30.57	34.22	38.09	42.17	46.47
0.010	%C	******	99.4	90.9	82.9	77.1	73.0	70.1	68.0	66.4	65.2	64.2	63.5	62.9	62.4	62.0	61.7	61.4	61.1	60.9	60.8
	F	1.499	0.922	0.699	0.586	0.521	0.481	0.453	0.434	0.420	0.410	0.402	0.396	0.391	0.387	0.384	0.381	0.379	0.377	0.375	0.374
	A	13.9	23.0	31.0	37.9	43.7	48.5	52.6	56.0	59.0	61.4	63.6	65.5	67.1	68.5	69.8	71.0	72.0	72.9	73.7	74.5
	K	******	1.28	1.95	2.74	3.66	4.74	5.98	7.38	8.95	10.68	12.59	14.66	16.91	19.33	21.92	24.68	27.62	30.73	34.01	37.46

CARRIERS 16 PICKS 9 ENDS 7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	99.9	78.7	63.0	53.9	48.4	44.9	42.5	40.8	39.5	38.6	37.9	37.4	36.9	36.6	36.3	36.0	35.8	35.7	35.5	35.4
	F	0.973	0.539	0.391	0.321	0.282	0.257	0.241	0.230	0.222	0.217	0.212	0.209	0.206	0.204	0.202	0.200	0.199	0.198	0.197	0.196
	A	11.2	20.5	28.9	36.1	42.1	47.2	51.5	55.1	58.2	60.8	63.0	65.0	66.7	68.2	69.5	70.7	71.7	72.7	73.5	74.3
	K	1.07	2.12	3.33	4.77	6.46	8.43	10.70	13.28	16.17	19.39	22.92	26.79	30.97	35.49	40.33	45.50	51.00	56.83	62.99	69.48
0.004	%C	******	91.4	76.7	67.0	60.8	56.7	53.9	51.9	50.5	49.4	48.5	47.9	47.3	46.9	46.6	46.3	46.0	45.8	45.6	45.5
	F	1.255	0.707	0.517	0.425	0.374	0.342	0.321	0.307	0.296	0.288	0.283	0.278	0.274	0.271	0.269	0.267	0.265	0.264	0.263	0.262
	A	11.6	20.9	29.2	36.3	42.4	47.4	51.7	55.3	58.3	60.9	63.1	65.0	66.7	68.2	69.5	70.7	71.7	72.7	73.5	74.3
	K	******	1.62	2.54	3.62	4.90	6.39	8.10	10.04	12.22	14.64	17.30	20.21	23.36	26.76	30.40	34.29	38.42	42.81	47.43	52.31
0.005	%C	******	98.3	87.0	77.8	71.4	67.1	64.1	61.9	60.3	59.1	58.1	57.4	56.8	56.3	55.9	55.6	55.3	55.1	54.9	54.7
	F	1.518	0.869	0.640	0.529	0.466	0.426	0.401	0.383	0.370	0.360	0.353	0.347	0.343	0.339	0.336	0.334	0.332	0.330	0.328	0.327
	A	12.0	21.2	29.5	36.6	42.6	47.6	51.8	55.4	58.4	61.0	63.2	65.1	66.8	68.3	69.6	70.7	71.8	72.7	73.6	74.4
	K	******	1.32	2.06	2.93	3.96	5.16	6.54	8.10	9.85	11.80	13.93	16.27	18.79	21.52	24.44	27.56	30.88	34.39	38.10	42.01
0.006	%C	******	******	94.3	86.3	80.3	76.0	72.9	70.7	69.0	67.7	66.7	65.9	65.3	64.8	64.4	64.0	63.7	63.5	63.3	63.1
	F	1.766	1.027	0.761	0.630	0.556	0.510	0.480	0.459	0.443	0.432	0.423	0.416	0.411	0.407	0.403	0.400	0.398	0.396	0.394	0.392
	A	12.4	21.6	29.8	36.8	42.8	47.8	52.0	55.5	58.5	61.1	63.3	65.2	66.9	68.3	69.6	70.8	71.8	72.8	73.6	74.4
	K	******	******	1.75	2.48	3.34	4.34	5.50	6.80	8.27	9.90	11.69	13.64	15.75	18.03	20.47	23.07	25.84	28.78	31.88	35.14
0.007	%C	******	******	98.5	92.8	87.5	83.5	80.5	78.3	76.6	75.3	74.3	73.5	72.9	72.4	71.9	71.6	71.3	71.0	70.8	70.6
	F	1.999	1.180	0.879	0.731	0.646	0.594	0.559	0.534	0.517	0.503	0.493	0.486	0.479	0.474	0.470	0.467	0.464	0.462	0.460	0.458
	A	12.7	21.9	30.1	37.1	43.0	48.0	52.1	55.6	58.6	61.2	63.4	65.3	66.9	68.4	69.7	70.8	71.9	72.8	73.6	74.4
	K	******	******	1.52	2.15	2.89	3.76	4.75	5.88	7.14	8.54	10.08	11.76	13.57	15.53	17.63	19.87	22.25	24.77	27.43	30.24
0.008	%C	******	******	100.0	97.1	93.0	89.5	86.8	84.8	83.2	81.9	80.9	80.2	79.5	79.0	78.6	78.2	77.9	77.7	77.5	77.3
	F	2.219	1.329	0.996	0.831	0.736	0.677	0.637	0.610	0.590	0.575	0.563	0.555	0.548	0.542	0.537	0.533	0.530	0.527	0.525	0.523
	A	13.1	22.3	30.4	37.4	43.2	48.2	52.3	55.8	58.7	61.3	63.4	65.3	67.0	68.4	69.7	70.9	71.9	72.8	73.7	74.4
	K	******	******	1.35	1.91	2.56	3.32	4.20	5.19	6.30	7.53	8.88	10.35	11.94	13.66	15.50	17.47	19.55	21.76	24.10	26.56
0.010	%C	******	******	******	******	99.2	97.5	95.7	94.2	93.0	92.0	91.2	90.5	90.0	89.6	89.2	88.9	88.6	88.4	88.2	88.0
	F	2.623	1.614	1.223	1.026	0.913	0.841	0.793	0.760	0.735	0.717	0.703	0.693	0.684	0.677	0.671	0.666	0.662	0.659	0.656	0.654
	A	13.9	23.0	31.0	37.9	43.7	48.5	52.6	56.0	59.0	61.4	63.6	65.5	67.1	68.5	69.8	71.0	72.0	72.9	73.7	74.5
	K	******	******	******	******	2.09	2.71	3.42	4.22	5.11	6.10	7.19	8.38	9.66	11.04	12.52	14.10	15.78	17.56	19.43	21.41

CARRIERS 16 PICKS 9 ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	94.7	80.6	70.7	64.3	60.0	57.1	55.0	53.5	52.3	51.4	50.7	50.2	49.7	49.3	49.0	48.8	48.6	48.4	48.2
	F	1.391	0.770	0.559	0.459	0.402	0.368	0.345	0.329	0.318	0.309	0.303	0.298	0.294	0.291	0.288	0.286	0.284	0.283	0.282	0.280
	A	11.2	20.5	28.9	36.1	42.1	47.2	51.5	55.1	58.2	60.8	63.0	65.0	66.7	68.2	69.5	70.7	71.7	72.7	73.5	74.3
	K	******	1.48	2.33	3.34	4.52	5.90	7.49	9.30	11.32	13.57	16.05	18.75	21.68	24.84	28.23	31.85	35.70	39.78	44.10	48.64
0.004	%C	******	******	93.2	84.6	78.3	73.9	70.7	68.4	66.7	65.4	64.4	63.6	63.0	62.5	62.1	61.7	61.4	61.2	61.0	60.8
	F	1.793	1.010	0.738	0.608	0.534	0.489	0.459	0.438	0.423	0.412	0.404	0.397	0.392	0.388	0.384	0.381	0.379	0.377	0.375	0.374
	A	11.6	20.9	29.2	36.3	42.4	47.4	51.7	55.3	58.3	60.9	63.1	65.0	66.7	68.2	69.5	70.7	71.7	72.7	73.5	74.3
	K	******	******	1.78	2.53	3.43	4.47	5.67	7.03	8.56	10.25	12.11	14.15	16.35	18.73	21.28	24.00	26.90	29.96	33.20	36.62
0.005	%C	******	******	99.3	94.0	88.8	84.7	81.7	79.5	77.8	76.4	75.4	74.6	74.0	73.4	73.0	72.6	72.3	72.0	71.8	71.6
	F	2.169	1.242	0.914	0.755	0.665	0.609	0.572	0.547	0.528	0.515	0.504	0.496	0.490	0.484	0.480	0.477	0.474	0.471	0.469	0.467
	A	12.0	21.2	29.5	36.6	42.6	47.6	51.8	55.4	58.4	61.0	63.2	65.1	66.8	68.3	69.6	70.7	71.8	72.7	73.6	74.4
	K	******	******	1.44	2.05	2.77	3.61	4.58	5.67	6.90	8.26	9.75	11.39	13.16	15.06	17.11	19.29	21.61	24.07	26.67	29.41
0.006	%C	******	******	******	99.0	95.8	92.7	90.1	88.1	86.5	85.3	84.4	83.6	83.0	82.5	82.0	81.7	81.4	81.1	80.9	80.7
	F	2.523	1.467	1.087	0.901	0.795	0.729	0.685	0.655	0.633	0.617	0.605	0.595	0.587	0.581	0.576	0.572	0.568	0.565	0.563	0.561
	A	12.4	21.6	29.8	36.8	42.8	47.8	52.0	55.5	58.5	61.1	63.3	65.2	66.9	68.3	69.6	70.8	71.8	72.8	73.6	74.4
	K	******	******	******	1.73	2.34	3.04	3.85	4.76	5.79	6.93	8.18	9.55	11.02	12.62	14.33	16.15	18.09	20.14	22.31	24.60
0.007	%C	******	******	******	******	99.4	97.7	95.9	94.4	93.1	92.1	91.3	90.6	90.1	89.6	89.2	88.9	88.6	88.4	88.2	88.0
	F	2.856	1.686	1.256	1.044	0.923	0.848	0.798	0.763	0.738	0.719	0.705	0.694	0.685	0.678	0.672	0.667	0.663	0.659	0.657	0.654
	A	12.7	21.9	30.1	37.1	43.0	48.0	52.1	55.6	58.6	61.2	63.4	65.3	66.9	68.4	69.7	70.8	71.9	72.8	73.6	74.4
	K	******	******	******	******	2.03	2.63	3.33	4.12	5.00	5.98	7.06	8.23	9.50	10.87	12.34	13.91	15.57	17.34	19.20	21.17
0.008	%C	******	******	******	******	******	99.9	99.2	98.3	97.5	96.8	96.2	95.7	95.3	94.9	94.6	94.3	94.1	93.9	93.8	93.6
	F	3.170	1.898	1.423	1.187	1.051	0.966	0.910	0.871	0.842	0.821	0.805	0.792	0.782	0.774	0.768	0.762	0.757	0.754	0.750	0.747
	A	13.1	22.3	30.4	37.4	43.2	48.2	52.3	55.8	58.7	61.3	63.4	65.3	67.0	68.4	69.7	70.9	71.9	72.8	73.7	74.4
	K	******	******	******	******	******	2.33	2.94	3.63	4.41	5.27	6.21	7.24	8.36	9.56	10.85	12.23	13.69	15.24	16.87	18.59
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	100.0	99.9	99.9	99.8	99.8	99.7	99.7	99.6	99.6
	F	3.748	2.305	1.748	1.466	1.304	1.201	1.133	1.085	1.051	1.025	1.005	0.989	0.977	0.967	0.959	0.952	0.946	0.942	0.938	0.934
	A	13.9	23.0	31.0	37.9	43.7	48.5	52.6	56.0	59.0	61.4	63.6	65.5	67.1	68.5	69.8	71.0	72.0	72.9	73.7	74.5
	K	******	******	******	******	******	******	******	******	******	******	******	5.86	6.76	7.73	8.77	9.87	11.05	12.29	13.60	14.99

		CARRIERS 16	PICKS 15	ENDS 4																	
STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	81.9	56.4	46.1	41.2	38.5	36.9	35.9	35.2	34.7	34.4	34.1	33.9	33.7	33.6	33.5	33.4	33.3	33.3	33.2	33.2
	F	0.575	0.340	0.266	0.233	0.216	0.206	0.199	0.195	0.192	0.190	0.188	0.187	0.186	0.185	0.184	0.184	0.184	0.183	0.183	0.183
	A	18.3	32.0	42.6	50.5	56.4	61.0	64.5	67.3	69.6	71.5	73.0	74.4	75.5	76.5	77.3	78.1	78.8	79.4	79.9	80.4
	K	1.93	4.09	6.93	10.60	15.16	20.64	27.07	34.44	42.77	52.06	62.31	73.52	85.69	98.82	112.92	127.98	144.00	160.98	178.93	197.84
0.004	%C	93.4	69.4	58.0	52.4	49.2	47.3	46.1	45.2	44.6	44.2	43.9	43.6	43.4	43.3	43.1	43.0	42.9	42.9	42.8	42.8
	F	0.742	0.447	0.352	0.310	0.287	0.274	0.266	0.260	0.256	0.253	0.251	0.249	0.248	0.247	0.246	0.245	0.245	0.244	0.244	0.243
	A	18.9	32.5	42.9	50.8	56.7	61.1	64.6	67.4	69.7	71.5	73.1	74.4	75.5	76.5	77.4	78.1	78.8	79.4	80.0	80.4
	K	1.50	3.14	5.30	8.07	11.52	15.66	20.51	26.07	32.34	39.34	47.05	55.49	64.65	74.52	85.13	96.45	108.49	121.26	134.75	148.97
0.005	%C	99.0	79.9	68.3	62.3	58.8	56.7	55.3	54.4	53.7	53.2	52.9	52.6	52.4	52.2	52.0	51.9	51.8	51.7	51.6	51.6
	F	0.900	0.552	0.437	0.386	0.358	0.342	0.332	0.325	0.320	0.316	0.313	0.311	0.310	0.308	0.307	0.307	0.306	0.305	0.305	0.304
	A	19.5	32.9	43.3	51.0	56.9	61.3	64.8	67.5	69.7	71.6	73.1	74.4	75.6	76.6	77.4	78.2	78.8	79.4	80.0	80.5
	K	1.25	2.57	4.32	6.56	9.34	12.67	16.57	21.04	26.09	31.71	37.90	44.67	52.02	59.95	68.45	77.53	87.19	97.43	108.25	119.64
0.006	%C	******	88.0	77.1	71.0	67.4	65.2	63.7	62.7	62.0	61.5	61.1	60.8	60.5	60.3	60.2	60.0	59.9	59.8	59.7	59.7
	F	1.049	0.654	0.521	0.461	0.429	0.410	0.398	0.389	0.384	0.379	0.376	0.374	0.372	0.370	0.369	0.368	0.367	0.366	0.366	0.365
	A	20.1	33.4	43.7	51.3	57.1	61.4	64.9	67.6	69.8	71.7	73.2	74.5	75.6	76.6	77.4	78.2	78.9	79.5	80.0	80.5
	K	******	2.20	3.66	5.55	7.88	10.68	13.95	17.69	21.92	26.62	31.80	37.46	43.61	50.23	57.34	64.92	72.99	81.54	90.58	100.09
0.007	%C	******	93.9	84.4	78.5	74.9	72.7	71.2	70.2	69.4	68.9	68.5	68.2	67.9	67.7	67.5	67.4	67.3	67.2	67.1	67.0
	F	1.191	0.753	0.605	0.536	0.499	0.477	0.463	0.454	0.447	0.442	0.439	0.436	0.434	0.432	0.430	0.429	0.428	0.427	0.426	0.426
	A	20.7	33.9	44.0	51.6	57.3	61.6	65.0	67.7	69.9	71.7	73.2	74.5	75.7	76.6	77.5	78.2	78.9	79.5	80.0	80.5
	K	******	1.93	3.20	4.83	6.85	9.26	12.08	15.30	18.94	22.99	27.44	32.31	37.60	43.29	49.40	55.92	62.85	70.20	77.95	86.13
0.008	%C	******	97.8	90.2	84.8	81.5	79.3	77.8	76.8	76.1	75.5	75.1	74.8	74.5	74.3	74.2	74.0	73.9	73.8	73.7	73.6
	F	1.325	0.851	0.687	0.611	0.569	0.545	0.529	0.518	0.511	0.505	0.501	0.498	0.495	0.493	0.492	0.490	0.489	0.488	0.487	0.487
	A	21.2	34.3	44.4	51.8	57.5	61.8	65.1	67.8	70.0	71.8	73.3	74.6	75.7	76.7	77.5	78.2	78.9	79.5	80.0	80.5
	K	******	1.72	2.85	4.29	6.07	8.19	10.67	13.51	16.71	20.26	24.18	28.45	33.09	38.09	43.44	49.16	55.24	61.69	68.49	75.65
0.010	%C	************		97.7	94.1	91.5	89.7	88.4	87.6	86.9	86.4	86.0	85.7	85.5	85.3	85.1	85.0	84.9	84.8	84.7	84.7
	F	1.574	1.039	0.848	0.758	0.709	0.679	0.660	0.647	0.638	0.631	0.626	0.622	0.619	0.616	0.614	0.613	0.611	0.610	0.609	0.608
	A	22.4	35.3	45.0	52.3	57.8	62.1	65.4	68.0	70.1	71.9	73.4	74.7	75.8	76.7	77.6	78.3	79.0	79.5	80.1	80.6
	K	************		2.36	3.54	4.98	6.70	8.71	11.00	13.58	16.45	19.60	23.05	26.78	30.80	35.11	39.71	44.60	49.77	55.24	60.99

CARRIERS 16 PICKS 15 ENDS 7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	83.6	71.4	65.0	61.3	59.1	57.6	56.6	55.9	55.4	55.0	54.7	54.5	54.3	54.1	54.0	53.9	53.8	53.8	53.7
	F	1.006	0.595	0.466	0.408	0.378	0.360	0.349	0.341	0.336	0.332	0.329	0.327	0.325	0.324	0.323	0.322	0.321	0.320	0.320	0.319
	A	18.3	32.0	42.6	50.5	56.4	61.0	64.5	67.3	69.6	71.5	73.0	74.4	75.5	76.5	77.3	78.1	78.8	79.4	79.9	80.4
	K	******	2.34	3.96	6.06	8.66	11.80	15.47	19.68	24.44	29.75	35.60	42.01	48.96	56.47	64.52	73.13	82.28	91.99	102.25	113.05
0.004	%C	******	95.3	85.3	79.0	75.3	72.9	71.4	70.3	69.5	69.0	68.5	68.2	67.9	67.7	67.6	67.4	67.3	67.2	67.1	67.0
	F	1.299	0.782	0.616	0.542	0.503	0.480	0.465	0.455	0.448	0.443	0.439	0.436	0.434	0.432	0.430	0.429	0.428	0.427	0.427	0.426
	A	18.9	32.5	42.9	50.8	56.7	61.1	64.6	67.4	69.7	71.5	73.1	74.4	75.5	76.5	77.4	78.1	78.8	79.4	80.0	80.4
	K	******	1.80	3.03	4.61	6.58	8.95	11.72	14.90	18.48	22.48	26.89	31.71	36.94	42.59	48.64	55.11	62.00	69.29	77.00	85.12
0.005	%C	******	99.9	94.5	89.4	86.1	83.9	82.4	81.4	80.6	80.0	79.6	79.3	79.0	78.8	78.6	78.5	78.4	78.3	78.2	78.1
	F	1.575	0.965	0.765	0.675	0.627	0.599	0.580	0.568	0.560	0.553	0.549	0.545	0.542	0.540	0.538	0.536	0.535	0.534	0.533	0.532
	A	19.5	32.9	43.3	51.0	56.9	61.3	64.8	67.5	69.7	71.6	73.1	74.4	75.6	76.6	77.4	78.2	78.8	79.4	80.0	80.5
	K	******	1.47	2.47	3.75	5.34	7.24	9.47	12.02	14.91	18.12	21.66	25.53	29.73	34.26	39.12	44.30	49.82	55.67	61.85	68.37
0.006	%C	******	******	99.2	96.3	93.8	92.0	90.7	89.8	89.2	88.7	88.3	88.0	87.8	87.6	87.4	87.3	87.2	87.1	87.0	87.0
	F	1.836	1.144	0.913	0.807	0.751	0.717	0.696	0.681	0.671	0.664	0.658	0.654	0.650	0.648	0.645	0.644	0.642	0.641	0.640	0.639
	A	20.1	33.4	43.7	51.3	57.1	61.4	64.9	67.6	69.8	71.7	73.2	74.5	75.6	76.6	77.4	78.2	78.9	79.5	80.0	80.5
	K	******	******	2.09	3.17	4.50	6.10	7.97	10.11	12.52	15.21	18.17	21.41	24.92	28.70	32.76	37.10	41.71	46.60	51.76	57.19
0.007	%C	******	******	******	99.6	98.4	97.3	96.4	95.8	95.3	94.9	94.6	94.4	94.2	94.0	93.9	93.8	93.7	93.6	93.6	93.5
	F	2.084	1.318	1.058	0.938	0.874	0.836	0.811	0.794	0.783	0.774	0.768	0.763	0.759	0.755	0.753	0.751	0.749	0.748	0.746	0.745
	A	20.7	33.9	44.0	51.6	57.3	61.6	65.0	67.7	69.9	71.7	73.2	74.5	75.7	76.6	77.5	78.2	78.9	79.5	80.0	80.5
	K	******	******	******	2.76	3.91	5.29	6.90	8.75	10.82	13.13	15.68	18.46	21.48	24.74	28.23	31.95	35.91	40.11	44.55	49.21
0.008	%C	******	******	******	******	100.0	99.8	99.5	99.1	98.9	98.7	98.5	98.3	98.2	98.1	98.1	98.0	97.9	97.9	97.8	97.8
	F	2.318	1.489	1.201	1.068	0.996	0.954	0.926	0.907	0.894	0.884	0.877	0.871	0.867	0.863	0.860	0.858	0.856	0.854	0.853	0.852
	A	21.2	34.3	44.4	51.8	57.5	61.8	65.1	67.8	70.0	71.8	73.3	74.6	75.7	76.7	77.5	78.2	78.9	79.5	80.0	80.5
	K	******	******	******	******	3.47	4.68	6.10	7.72	9.55	11.58	13.82	16.26	18.91	21.76	24.83	28.09	31.57	35.25	39.14	43.23
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	2.754	1.819	1.484	1.326	1.240	1.189	1.155	1.133	1.116	1.105	1.096	1.089	1.083	1.079	1.075	1.072	1.070	1.068	1.066	1.064
	A	22.4	35.3	45.0	52.3	57.8	62.1	65.4	68.0	70.1	71.9	73.4	74.7	75.8	76.7	77.6	78.3	79.0	79.5	80.1	80.6
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

	CARRIERS 16	PICKS 15	ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	97.7	88.8	82.6	78.8	76.4	74.9	73.8	73.0	72.4	72.0	71.6	71.4	71.1	71.0	70.8	70.7	70.6	70.5	70.4
	F	1.436	0.850	0.665	0.583	0.540	0.515	0.499	0.488	0.480	0.475	0.471	0.467	0.465	0.463	0.461	0.460	0.459	0.458	0.457	0.456
	A	18.3	32.0	42.6	50.5	56.4	61.0	64.5	67.3	69.6	71.5	73.0	74.4	75.5	76.5	77.3	78.1	78.8	79.4	79.9	80.4
	K	******	1.64	2.77	4.24	6.06	8.26	10.83	13.78	17.11	20.82	24.92	29.41	34.27	39.53	45.17	51.19	57.60	64.39	71.57	79.14
0.004	%C	******	******	98.6	94.9	92.1	90.1	88.7	87.7	87.0	86.5	86.1	85.8	85.5	85.3	85.2	85.0	84.9	84.8	84.7	84.7
	F	1.856	1.118	0.881	0.774	0.718	0.685	0.664	0.650	0.640	0.633	0.627	0.623	0.620	0.617	0.615	0.613	0.612	0.610	0.609	0.608
	A	18.9	32.5	42.9	50.8	56.7	61.1	64.6	67.4	69.7	71.5	73.1	74.4	75.5	76.5	77.4	78.1	78.8	79.4	80.0	80.4
	K	******	******	2.12	3.23	4.61	6.26	8.20	10.43	12.94	15.74	18.82	22.20	25.86	29.81	34.05	38.58	43.40	48.50	53.90	59.59
0.005	%C	******	******	******	99.9	98.9	97.9	97.1	96.5	96.0	95.6	95.3	95.1	94.9	94.8	94.6	94.5	94.5	94.4	94.3	94.3
	F	2.251	1.379	1.094	0.964	0.896	0.855	0.829	0.812	0.799	0.790	0.784	0.779	0.774	0.771	0.768	0.766	0.764	0.763	0.762	0.761
	A	19.5	32.9	43.3	51.0	56.9	61.3	64.8	67.5	69.7	71.6	73.1	74.4	75.6	76.6	77.4	78.2	78.8	79.4	80.0	80.5
	K	******	******	******	2.62	3.74	5.07	6.63	8.42	10.43	12.68	15.16	17.87	20.81	23.98	27.38	31.01	34.88	38.97	43.30	47.86
0.006	%C	******	******	******	******	******	******	100.0	99.9	99.8	99.7	99.6	99.6	99.5	99.4	99.4	99.4	99.3	99.3	99.3	99.2
	F	2.624	1.634	1.304	1.153	1.072	1.025	0.994	0.973	0.959	0.948	0.940	0.934	0.929	0.925	0.922	0.919	0.917	0.915	0.914	0.913
	A	20.1	33.4	43.7	51.3	57.1	61.4	64.9	67.6	69.8	71.7	73.2	74.5	75.6	76.6	77.4	78.2	78.9	79.5	80.0	80.5
	K	******	******	******	******	******	******	5.58	7.08	8.77	10.65	12.72	14.99	17.44	20.09	22.93	25.97	29.20	32.62	36.23	40.04
0.007	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	2.977	1.883	1.511	1.340	1.248	1.194	1.159	1.135	1.118	1.106	1.097	1.089	1.084	1.079	1.076	1.073	1.070	1.068	1.066	1.065
	A	20.7	33.9	44.0	51.6	57.3	61.6	65.0	67.7	69.9	71.7	73.2	74.5	75.7	76.6	77.5	78.2	78.9	79.5	80.0	80.5
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.008	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	3.312	2.127	1.716	1.526	1.424	1.362	1.323	1.296	1.277	1.263	1.253	1.245	1.238	1.233	1.229	1.226	1.223	1.220	1.218	1.217
	A	21.2	34.3	44.4	51.8	57.5	61.8	65.1	67.8	70.0	71.8	73.3	74.6	75.7	76.7	77.5	78.2	78.9	79.5	80.0	80.5
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	3.935	2.599	2.120	1.895	1.772	1.698	1.650	1.618	1.595	1.578	1.565	1.555	1.547	1.541	1.536	1.532	1.528	1.525	1.523	1.521
	A	22.4	35.3	45.0	52.3	57.8	62.1	65.4	68.0	70.1	71.9	73.4	74.7	75.8	76.7	77.6	78.3	79.0	79.5	80.1	80.6
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

											CARRIERS 24		PICKS 3	ENDS 4							
STR.DIA.										DIAMETER OVER DIELECTRIC											
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	96.7	68.0	50.4	40.0	33.2	28.4	25.0	22.3	20.2	18.5	17.2	16.1	15.1	14.3	13.6	13.0	12.5	12.0	11.6	11.3
	F	0.819	0.434	0.296	0.225	0.183	0.154	0.134	0.118	0.107	0.097	0.090	0.084	0.079	0.074	0.071	0.067	0.065	0.062	0.060	0.058
	A	2.5	4.8	7.0	9.2	11.4	13.5	15.6	17.7	19.7	21.7	23.6	25.5	27.3	29.0	30.7	32.3	33.9	35.4	36.9	38.3
	K	1.22	2.32	3.43	4.55	5.70	6.87	8.06	9.30	10.57	11.88	13.24	14.64	16.10	17.61	19.18	20.81	22.50	24.26	26.08	27.97
0.004	%C	******	81.3	62.8	50.7	42.5	36.7	32.3	29.0	26.4	24.2	22.5	21.0	19.8	18.8	17.9	17.1	16.4	15.9	15.3	14.9
	F	1.055	0.568	0.390	0.298	0.242	0.204	0.177	0.157	0.142	0.130	0.120	0.111	0.105	0.099	0.094	0.090	0.086	0.083	0.080	0.077
	A	2.6	4.8	7.1	9.3	11.5	13.6	15.7	17.8	19.8	21.8	23.7	25.5	27.3	29.1	30.8	32.4	34.0	35.5	37.0	38.4
	K	******	1.77	2.61	3.45	4.31	5.18	6.08	7.01	7.96	8.95	9.97	11.02	12.12	13.26	14.43	15.66	16.93	18.25	19.62	21.04
0.005	%C	******	90.8	73.1	60.1	51.0	44.3	39.2	35.3	32.2	29.7	27.6	25.8	24.4	23.1	22.0	21.1	20.3	19.6	18.9	18.4
	F	1.275	0.697	0.481	0.369	0.300	0.254	0.221	0.196	0.177	0.161	0.149	0.139	0.130	0.123	0.117	0.112	0.107	0.103	0.100	0.097
	A	2.7	4.9	7.2	9.4	11.5	13.7	15.8	17.8	19.9	21.8	23.7	25.6	27.4	29.1	30.8	32.5	34.0	35.6	37.0	38.4
	K	******	1.45	2.11	2.79	3.47	4.18	4.90	5.64	6.40	7.19	8.01	8.85	9.73	10.64	11.59	12.57	13.58	14.64	15.74	16.88
0.006	%C	******	96.8	81.5	68.5	58.7	51.4	45.7	41.3	37.8	34.9	32.5	30.5	28.8	27.3	26.1	25.0	24.0	23.2	22.5	21.8
	F	1.480	0.822	0.570	0.438	0.357	0.303	0.263	0.234	0.211	0.193	0.178	0.166	0.156	0.148	0.140	0.134	0.128	0.124	0.119	0.116
	A	2.8	5.0	7.3	9.5	11.6	13.8	15.9	17.9	19.9	21.9	23.8	25.7	27.5	29.2	30.9	32.5	34.1	35.6	37.1	38.5
	K	******	1.23	1.78	2.34	2.92	3.50	4.11	4.72	5.36	6.02	6.70	7.41	8.14	8.90	9.69	10.51	11.36	12.24	13.15	14.10
0.007	%C	******	99.7	88.3	75.7	65.6	57.9	51.8	47.0	43.0	39.8	37.2	34.9	33.0	31.4	30.0	28.8	27.7	26.7	25.9	25.1
	F	1.673	0.942	0.658	0.507	0.414	0.351	0.306	0.272	0.245	0.224	0.207	0.193	0.182	0.172	0.163	0.156	0.150	0.144	0.139	0.135
	A	2.9	5.1	7.3	9.5	11.7	13.9	16.0	18.0	20.0	22.0	23.9	25.7	27.5	29.3	31.0	32.6	34.2	35.7	37.1	38.5
	K	******	1.07	1.55	2.03	2.52	3.02	3.54	4.07	4.62	5.18	5.77	6.37	7.00	7.65	8.33	9.03	9.76	10.52	11.31	12.12
0.008	%C	******	******	93.4	81.8	71.9	63.8	57.4	52.3	48.1	44.6	41.7	39.2	37.1	35.3	33.8	32.4	31.2	30.2	29.2	28.4
	F	1.854	1.058	0.743	0.574	0.469	0.399	0.347	0.309	0.279	0.256	0.236	0.220	0.207	0.196	0.186	0.178	0.171	0.164	0.159	0.154
	A	3.0	5.2	7.4	9.6	11.8	13.9	16.0	18.1	20.1	22.1	24.0	25.8	27.6	29.4	31.0	32.7	34.2	35.7	37.2	38.6
	K	******	******	1.37	1.79	2.22	2.66	3.12	3.58	4.06	4.56	5.07	5.60	6.15	6.72	7.31	7.93	8.57	9.23	9.92	10.63
0.010	%C	******	******	99.1	91.3	82.2	74.2	67.5	61.9	57.3	53.4	50.1	47.3	44.9	42.8	41.0	39.4	38.0	36.8	35.7	34.7
	F	2.186	1.279	0.907	0.705	0.578	0.492	0.430	0.383	0.347	0.317	0.294	0.274	0.258	0.244	0.232	0.222	0.213	0.205	0.198	0.192
	A	3.1	5.4	7.6	9.8	12.0	14.1	16.2	18.3	20.3	22.2	24.1	26.0	27.8	29.5	31.2	32.8	34.3	35.9	37.3	38.7
	K	******	******	1.12	1.46	1.81	2.16	2.52	2.89	3.28	3.68	4.09	4.51	4.96	5.41	5.89	6.38	6.90	7.43	7.98	8.55

CARRIERS 24 PICKS 3 ENDS 7

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	94.2	76.8	63.3	53.7	46.7	41.3	37.2	33.9	31.2	29.0	27.2	25.6	24.3	23.2	22.2	21.3	20.6	19.9	19.3
	F	1.434	0.759	0.518	0.394	0.320	0.270	0.234	0.207	0.187	0.171	0.157	0.147	0.138	0.130	0.123	0.118	0.113	0.109	0.105	0.102
	A	2.5	4.8	7.0	9.2	11.4	13.5	15.6	17.7	19.7	21.7	23.6	25.5	27.3	29.0	30.7	32.3	33.9	35.4	36.9	38.3
	K	******	1.33	1.96	2.60	3.26	3.92	4.61	5.31	6.04	6.79	7.56	8.37	9.20	10.06	10.96	11.89	12.86	13.86	14.90	15.98
0.004	%C	******	100.0	89.9	77.1	66.7	58.7	52.4	47.5	43.5	40.2	37.5	35.2	33.2	31.6	30.1	28.9	27.8	26.8	26.0	25.2
	F	1.846	0.994	0.682	0.521	0.423	0.357	0.310	0.275	0.248	0.227	0.209	0.195	0.183	0.173	0.164	0.157	0.150	0.145	0.140	0.135
	A	2.6	4.8	7.1	9.3	11.5	13.6	15.7	17.8	19.8	21.8	23.7	25.5	27.3	29.1	30.8	32.4	34.0	35.5	37.0	38.4
	K	******	1.01	1.49	1.97	2.46	2.96	3.48	4.01	4.55	5.11	5.70	6.30	6.93	7.57	8.25	8.95	9.67	10.43	11.21	12.02
0.005	%C	******	******	97.5	87.4	77.4	69.1	62.3	56.8	52.3	48.5	45.4	42.7	40.4	38.5	36.8	35.3	34.0	32.9	31.8	30.9
	F	2.231	1.220	0.842	0.645	0.525	0.444	0.386	0.343	0.309	0.282	0.261	0.243	0.228	0.216	0.205	0.196	0.188	0.181	0.174	0.169
	A	2.7	4.9	7.2	9.4	11.5	13.7	15.8	17.8	19.9	21.8	23.7	25.6	27.4	29.1	30.8	32.5	34.0	35.6	37.0	38.4
	K	******	******	1.21	1.59	1.98	2.39	2.80	3.22	3.66	4.11	4.58	5.06	5.56	6.08	6.62	7.18	7.76	8.37	8.99	9.64
0.006	%C	******	******	100.0	94.6	85.9	77.9	70.9	65.1	60.2	56.1	52.7	49.7	47.2	45.0	43.1	41.4	39.9	38.6	37.4	36.4
	F	2.591	1.438	0.998	0.767	0.625	0.529	0.461	0.409	0.369	0.338	0.312	0.291	0.273	0.258	0.245	0.234	0.225	0.216	0.209	0.203
	A	2.8	5.0	7.3	9.5	11.6	13.8	15.9	17.9	19.9	21.9	23.8	25.7	27.5	29.2	30.9	32.5	34.1	35.6	37.1	38.5
	K	******	******	1.02	1.34	1.67	2.00	2.35	2.70	3.06	3.44	3.83	4.23	4.65	5.08	5.54	6.00	6.49	6.99	7.52	8.06
0.007	%C	******	******	******	98.7	92.4	85.1	78.4	72.5	67.4	63.1	59.4	56.2	53.5	51.1	49.0	47.1	45.5	44.1	42.8	41.6
	F	2.928	1.648	1.151	0.887	0.724	0.614	0.535	0.475	0.429	0.393	0.363	0.338	0.318	0.301	0.286	0.273	0.262	0.252	0.244	0.236
	A	2.9	5.1	7.3	9.5	11.7	13.9	16.0	18.0	20.0	22.0	23.9	25.7	27.5	29.3	31.0	32.6	34.2	35.7	37.1	38.5
	K	******	******	******	1.16	1.44	1.73	2.02	2.33	2.64	2.96	3.30	3.64	4.00	4.37	4.76	5.16	5.58	6.01	6.46	6.93
0.008	%C	******	******	******	******	96.8	90.8	84.6	78.9	73.9	69.5	65.6	62.3	59.4	56.8	54.6	52.6	50.8	49.3	47.9	46.6
	F	3.245	1.852	1.299	1.004	0.822	0.697	0.608	0.541	0.489	0.447	0.414	0.386	0.362	0.343	0.326	0.311	0.299	0.288	0.278	0.269
	A	3.0	5.2	7.4	9.6	11.8	13.9	16.0	18.1	20.1	22.1	24.0	25.8	27.6	29.4	31.0	32.7	34.2	35.7	37.2	38.6
	K	******	******	******	******	1.27	1.52	1.78	2.05	2.32	2.60	2.90	3.20	3.51	3.84	4.18	4.53	4.90	5.28	5.67	6.08
0.010	%C	******	******	******	******	******	98.1	93.9	89.1	84.5	80.2	76.4	72.9	69.9	67.1	64.7	62.5	60.6	58.9	57.3	55.9
	F	3.825	2.238	1.587	1.233	1.012	0.862	0.753	0.670	0.606	0.555	0.514	0.480	0.451	0.427	0.406	0.388	0.372	0.359	0.347	0.336
	A	3.1	5.4	7.6	9.8	12.0	14.1	16.2	18.3	20.3	22.2	24.1	26.0	27.8	29.5	31.2	32.8	34.3	35.9	37.3	38.7
	K	******	******	******	******	******	1.23	1.44	1.65	1.87	2.10	2.34	2.58	2.83	3.09	3.37	3.65	3.94	4.25	4.56	4.89

CARRIERS 24 PICKS 3 ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	******	93.2	80.9	70.5	62.2	55.7	50.5	46.3	42.8	39.9	37.5	35.4	33.7	32.1	30.8	29.7	28.6	27.7	26.9
	F	2.048	1.085	0.740	0.564	0.457	0.385	0.334	0.296	0.267	0.244	0.225	0.209	0.197	0.186	0.176	0.168	0.161	0.155	0.150	0.145
	A	2.5	4.8	7.0	9.2	11.4	13.5	15.6	17.7	19.7	21.7	23.6	25.5	27.3	29.0	30.7	32.3	33.9	35.4	36.9	38.3
	K	******	******	1.37	1.82	2.28	2.75	3.23	3.72	4.23	4.75	5.29	5.86	6.44	7.04	7.67	8.32	9.00	9.70	10.43	11.19
0.004	%C	******	******	99.9	93.5	84.3	76.0	69.0	63.2	58.3	54.3	50.9	47.9	45.4	43.3	41.4	39.8	38.3	37.1	35.9	34.9
	F	2.637	1.420	0.974	0.744	0.604	0.510	0.443	0.393	0.355	0.324	0.299	0.278	0.261	0.247	0.235	0.224	0.215	0.207	0.200	0.193
	A	2.6	4.8	7.1	9.3	11.5	13.6	15.7	17.8	19.8	21.8	23.7	25.5	27.3	29.1	30.8	32.4	34.0	35.5	37.0	38.4
	K	******	******	1.04	1.38	1.72	2.07	2.43	2.80	3.19	3.58	3.99	4.41	4.85	5.30	5.77	6.26	6.77	7.30	7.85	8.41
0.005	%C	******	******	******	99.4	93.7	86.6	79.9	73.9	68.8	64.4	60.6	57.4	54.6	52.1	50.0	48.1	46.4	44.9	43.6	42.4
	F	3.187	1.743	1.203	0.922	0.750	0.634	0.551	0.489	0.441	0.403	0.373	0.347	0.326	0.308	0.293	0.279	0.268	0.258	0.249	0.241
	A	2.7	4.9	7.2	9.4	11.5	13.7	15.8	17.8	19.9	21.8	23.7	25.6	27.4	29.1	30.8	32.5	34.0	35.6	37.0	38.4
	K	******	******	******	1.11	1.39	1.67	1.96	2.26	2.56	2.88	3.20	3.54	3.89	4.26	4.63	5.03	5.43	5.86	6.30	6.75
0.006	%C	******	******	******	******	98.9	94.1	88.3	82.7	77.7	73.2	69.3	65.8	62.8	60.2	57.8	55.7	53.9	52.3	50.8	49.5
	F	3.701	2.054	1.426	1.096	0.893	0.756	0.658	0.585	0.528	0.482	0.446	0.415	0.390	0.369	0.351	0.335	0.321	0.309	0.299	0.289
	A	2.8	5.0	7.3	9.5	11.6	13.8	15.9	17.9	19.9	21.9	23.8	25.7	27.5	29.2	30.9	32.5	34.1	35.6	37.1	38.5
	K	******	******	******	******	1.17	1.40	1.64	1.89	2.14	2.41	2.68	2.96	3.26	3.56	3.87	4.20	4.54	4.89	5.26	5.64
0.007	%C	******	******	******	******	******	98.5	94.4	89.7	85.0	80.7	76.8	73.3	70.2	67.4	65.0	62.8	60.8	59.1	57.5	56.1
	F	4.183	2.355	1.644	1.267	1.034	0.877	0.764	0.679	0.613	0.561	0.519	0.483	0.454	0.429	0.408	0.390	0.374	0.360	0.348	0.337
	A	2.9	5.1	7.3	9.5	11.7	13.9	16.0	18.0	20.0	22.0	23.9	25.7	27.5	29.3	31.0	32.6	34.2	35.7	37.1	38.5
	K	******	******	******	******	******	1.21	1.42	1.63	1.85	2.07	2.31	2.55	2.80	3.06	3.33	3.61	3.91	4.21	4.52	4.85
0.008	%C	******	******	******	******	******	100.0	98.3	94.8	90.9	87.0	83.3	79.8	76.7	74.0	71.4	69.2	67.1	65.3	63.6	62.2
	F	4.636	2.645	1.856	1.435	1.174	0.996	0.869	0.773	0.698	0.639	0.591	0.551	0.518	0.490	0.466	0.445	0.427	0.411	0.397	0.385
	A	3.0	5.2	7.4	9.6	11.8	13.9	16.0	18.1	20.1	22.1	24.0	25.8	27.6	29.4	31.0	32.7	34.2	35.7	37.2	38.6
	K	******	******	******	******	******	1.07	1.25	1.43	1.62	1.82	2.03	2.24	2.46	2.69	2.93	3.17	3.43	3.69	3.97	4.25
0.010	%C	******	******	******	******	******	******	******	99.8	98.2	95.7	92.9	90.1	87.3	84.7	82.3	80.1	78.1	76.2	74.5	72.9
	F	5.465	3.197	2.267	1.762	1.446	1.231	1.075	0.958	0.866	0.793	0.734	0.685	0.644	0.609	0.580	0.554	0.532	0.512	0.495	0.480
	A	3.1	5.4	7.6	9.8	12.0	14.1	16.2	18.3	20.3	22.2	24.1	26.0	27.8	29.5	31.2	32.8	34.3	35.9	37.3	38.7
	K	******	******	******	******	******	******	******	1.16	1.31	1.47	1.63	1.81	1.98	2.17	2.36	2.55	2.76	2.97	3.19	3.42

CARRIERS 24 PICKS 9 ENDS 4

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	97.0	69.3	52.8	43.3	37.4	33.5	30.8	28.8	27.3	26.2	25.3	24.6	24.1	23.6	23.2	22.9	22.7	22.4	22.2	22.1
	F	0.826	0.446	0.313	0.247	0.209	0.185	0.168	0.156	0.148	0.141	0.136	0.132	0.129	0.126	0.124	0.122	0.121	0.119	0.118	0.117
	A	7.5	14.0	20.2	25.9	31.1	35.8	40.0	43.7	47.1	50.0	52.6	55.0	57.1	59.0	60.7	62.2	63.6	64.9	66.1	67.1
	K	1.23	2.38	3.63	5.00	6.52	8.23	10.14	12.26	14.60	17.18	19.99	23.05	26.35	29.89	33.69	37.74	42.04	46.59	51.40	56.46
0.004	%C	******	82.7	65.5	54.7	47.8	43.0	39.7	37.2	35.4	34.0	32.9	32.0	31.3	30.8	30.3	29.9	29.5	29.3	29.0	28.8
	F	1.064	0.584	0.413	0.327	0.277	0.245	0.223	0.208	0.196	0.188	0.181	0.176	0.171	0.168	0.165	0.163	0.161	0.159	0.157	0.156
	A	7.8	14.3	20.4	26.1	31.3	36.0	40.1	43.9	47.2	50.1	52.7	55.1	57.2	59.1	60.8	62.3	63.7	64.9	66.1	67.2
	K	******	1.82	2.76	3.79	4.94	6.23	7.66	9.26	11.03	12.96	15.08	17.38	19.86	22.53	25.39	28.43	31.66	35.09	38.70	42.50
0.005	%C	******	92.0	76.0	64.7	57.0	51.7	47.9	45.1	43.0	41.4	40.1	39.0	38.2	37.5	37.0	36.5	36.1	35.8	35.5	35.2
	F	1.286	0.717	0.510	0.406	0.345	0.305	0.278	0.259	0.245	0.234	0.226	0.219	0.214	0.210	0.206	0.203	0.201	0.199	0.197	0.195
	A	8.0	14.5	20.7	26.3	31.5	36.1	40.3	44.0	47.3	50.2	52.8	55.2	57.3	59.1	60.8	62.3	63.7	65.0	66.1	67.2
	K	******	1.49	2.24	3.07	3.99	5.03	6.18	7.46	8.88	10.44	12.14	13.98	15.97	18.11	20.40	22.85	25.44	28.18	31.08	34.13
0.006	%C	******	97.6	84.5	73.3	65.3	59.6	55.5	52.4	50.1	48.2	46.8	45.7	44.7	44.0	43.3	42.8	42.4	42.0	41.6	41.4
	F	1.494	0.847	0.606	0.483	0.411	0.365	0.333	0.310	0.293	0.281	0.271	0.263	0.257	0.251	0.247	0.244	0.241	0.238	0.236	0.234
	A	8.3	14.8	20.9	26.5	31.7	36.3	40.5	44.1	47.4	50.3	52.9	55.3	57.3	59.2	60.9	62.4	63.8	65.0	66.2	67.2
	K	******	1.26	1.89	2.59	3.36	4.22	5.19	6.26	7.45	8.75	10.17	11.71	13.38	15.17	17.08	19.12	21.29	23.58	26.00	28.54
0.007	%C	******	99.9	90.9	80.6	72.7	66.8	62.4	59.2	56.6	54.7	53.1	51.9	50.9	50.0	49.3	48.8	48.3	47.8	47.5	47.2
	F	1.690	0.971	0.699	0.560	0.477	0.424	0.387	0.361	0.342	0.327	0.315	0.306	0.299	0.293	0.288	0.284	0.281	0.278	0.275	0.273
	A	8.6	15.0	21.1	26.8	31.9	36.5	40.6	44.3	47.6	50.5	53.0	55.3	57.4	59.3	60.9	62.5	63.8	65.1	66.2	67.3
	K	******	1.10	1.64	2.24	2.91	3.65	4.48	5.41	6.43	7.55	8.77	10.10	11.53	13.07	14.71	16.46	18.32	20.29	22.37	24.56
0.008	%C	******	******	95.6	86.7	79.1	73.2	68.8	65.4	62.7	60.7	59.0	57.7	56.6	55.8	55.0	54.4	53.9	53.4	53.0	52.7
	F	1.874	1.092	0.791	0.635	0.542	0.482	0.441	0.411	0.390	0.373	0.360	0.350	0.342	0.335	0.329	0.325	0.321	0.317	0.315	0.312
	A	8.8	15.3	21.4	27.0	32.1	36.7	40.8	44.4	47.7	50.6	53.1	55.4	57.5	59.3	61.0	62.5	63.9	65.1	66.3	67.3
	K	******	******	1.46	1.98	2.57	3.22	3.95	4.77	5.66	6.65	7.72	8.88	10.14	11.49	12.93	14.47	16.10	17.83	19.65	21.56
0.010	%C	******	******	99.9	95.3	89.2	83.8	79.6	76.2	73.5	71.3	69.6	68.2	67.1	66.1	65.3	64.6	64.1	63.6	63.1	62.8
	F	2.212	1.323	0.968	0.782	0.671	0.598	0.548	0.512	0.485	0.465	0.449	0.436	0.426	0.418	0.411	0.405	0.401	0.396	0.393	0.390
	A	9.4	15.8	21.8	27.4	32.5	37.0	41.1	44.7	47.9	50.8	53.3	55.6	57.6	59.5	61.1	62.6	64.0	65.2	66.4	67.4
	K	******	******	1.20	1.62	2.09	2.62	3.21	3.87	4.59	5.38	6.25	7.18	8.19	9.28	10.44	11.68	12.99	14.37	15.84	17.38

CARRIERS 24 PICKS 9 ENDS 7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	95.2	79.6	67.8	59.8	54.2	50.2	47.2	45.0	43.3	41.9	40.8	40.0	39.2	38.7	38.2	37.7	37.4	37.1	36.8
	F	1.445	0.780	0.548	0.433	0.366	0.323	0.294	0.273	0.258	0.247	0.238	0.231	0.225	0.221	0.217	0.214	0.211	0.209	0.207	0.205
	A	7.5	14.0	20.2	25.9	31.1	35.8	40.0	43.7	47.1	50.0	52.6	55.0	57.1	59.0	60.7	62.2	63.6	64.9	66.1	67.1
	K	******	1.36	2.07	2.85	3.73	4.70	5.79	7.00	8.34	9.82	11.42	13.17	15.06	17.08	19.25	21.57	24.02	26.63	29.37	32.26
0.004	%C	******	******	92.3	81.7	73.5	67.4	62.9	59.5	56.9	54.9	53.3	52.0	51.0	50.1	49.4	48.8	48.3	47.9	47.5	47.2
	F	1.861	1.022	0.722	0.573	0.485	0.429	0.391	0.364	0.344	0.328	0.317	0.307	0.300	0.294	0.289	0.285	0.281	0.278	0.276	0.273
	A	7.8	14.3	20.4	26.1	31.3	36.0	40.1	43.9	47.2	50.1	52.7	55.1	57.2	59.1	60.8	62.3	63.7	64.9	66.1	67.2
	K	******	******	1.58	2.17	2.82	3.56	4.38	5.29	6.30	7.41	8.62	9.93	11.35	12.88	14.51	16.25	18.09	20.05	22.11	24.29
0.005	%C	******	******	98.9	91.6	84.2	78.3	73.7	70.1	67.3	65.2	63.4	62.0	60.9	59.9	59.1	58.5	57.9	57.4	57.0	56.7
	F	2.250	1.256	0.893	0.710	0.603	0.534	0.487	0.453	0.429	0.410	0.395	0.384	0.375	0.367	0.361	0.356	0.351	0.348	0.344	0.342
	A	8.0	14.5	20.7	26.3	31.5	36.1	40.3	44.0	47.3	50.2	52.8	55.2	57.3	59.1	60.8	62.3	63.7	65.0	66.1	67.2
	K	******	******	1.28	1.75	2.28	2.87	3.53	4.26	5.07	5.96	6.93	7.99	9.13	10.35	11.66	13.05	14.54	16.10	17.76	19.50
0.006	%C	******	******	******	97.6	92.1	86.9	82.6	79.1	76.3	74.1	72.3	70.8	69.6	68.6	67.8	67.1	66.5	66.0	65.6	65.2
	F	2.615	1.481	1.060	0.846	0.720	0.638	0.582	0.543	0.513	0.491	0.474	0.460	0.449	0.440	0.433	0.427	0.421	0.417	0.413	0.410
	A	8.3	14.8	20.9	26.5	31.7	36.3	40.5	44.1	47.4	50.3	52.9	55.3	57.3	59.2	60.9	62.4	63.8	65.0	66.2	67.2
	K	******	******	******	1.48	1.92	2.41	2.97	3.58	4.26	5.00	5.81	6.69	7.65	8.67	9.76	10.93	12.16	13.47	14.86	16.31
0.007	%C	******	******	******	100.0	97.3	93.3	89.6	86.4	83.8	81.7	79.9	78.5	77.3	76.3	75.4	74.7	74.1	73.6	73.2	72.8
	F	2.958	1.700	1.223	0.980	0.835	0.741	0.677	0.632	0.598	0.572	0.552	0.536	0.523	0.513	0.504	0.497	0.491	0.486	0.482	0.478
	A	8.6	15.0	21.1	26.8	31.9	36.5	40.6	44.3	47.6	50.5	53.0	55.3	57.4	59.3	60.9	62.5	63.8	65.1	66.2	67.3
	K	******	******	******	1.28	1.66	2.09	2.56	3.09	3.67	4.31	5.01	5.77	6.59	7.47	8.41	9.41	10.47	11.60	12.78	14.03
0.008	%C	******	******	******	******	99.7	97.6	94.8	92.2	89.9	87.9	86.3	84.9	83.8	82.9	82.0	81.3	80.8	80.2	79.8	79.4
	F	3.280	1.912	1.384	1.111	0.949	0.844	0.772	0.720	0.682	0.653	0.630	0.612	0.598	0.586	0.576	0.568	0.561	0.555	0.550	0.546
	A	8.8	15.3	21.4	27.0	32.1	36.7	40.8	44.4	47.7	50.6	53.1	55.4	57.5	59.3	61.0	62.5	63.9	65.1	66.3	67.3
	K	******	******	******	******	1.47	1.84	2.26	2.72	3.24	3.80	4.41	5.08	5.79	6.56	7.39	8.27	9.20	10.19	11.23	12.32
0.010	%C	******	******	******	******	******	******	99.8	98.9	97.7	96.5	95.4	94.4	93.5	92.8	92.1	91.6	91.1	90.6	90.2	89.9
	F	3.871	2.316	1.694	1.369	1.174	1.046	0.959	0.896	0.849	0.813	0.785	0.763	0.746	0.731	0.719	0.709	0.701	0.694	0.688	0.682
	A	9.4	15.8	21.8	27.4	32.5	37.0	41.1	44.7	47.9	50.8	53.3	55.6	57.6	59.5	61.1	62.6	64.0	65.2	66.4	67.4
	K	******	******	******	******	******	******	1.84	2.21	2.62	3.08	3.57	4.11	4.68	5.30	5.97	6.67	7.42	8.21	9.05	9.93

CARRIERS 24 | PICKS 9 | ENDS 10

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	****	****	95.3	85.4	77.2	71.0	66.4	62.9	60.2	58.1	56.4	55.1	54.0	53.1	52.3	51.7	51.2	50.7	50.4	50.0
	F	2.064	1.114	0.783	0.618	0.523	0.462	0.420	0.391	0.369	0.352	0.340	0.330	0.322	0.315	0.310	0.305	0.301	0.298	0.295	0.293
	A	7.5	14.0	20.2	25.9	31.1	35.8	40.0	43.7	47.1	50.0	52.6	55.0	57.1	59.0	60.7	62.2	63.6	64.9	66.1	67.1
	K	****	****	1.45	2.00	2.61	3.29	4.05	4.90	5.84	6.87	8.00	9.22	10.54	11.96	13.48	15.10	16.82	18.64	20.56	22.59
0.004	%C	****	****	****	96.7	90.6	85.0	80.5	76.9	74.1	71.8	70.0	68.5	67.3	66.3	65.5	64.8	64.2	63.7	63.2	62.9
	F	2.659	1.460	1.032	0.818	0.693	0.613	0.558	0.519	0.491	0.469	0.452	0.439	0.428	0.420	0.413	0.407	0.402	0.397	0.394	0.391
	A	7.8	14.3	20.4	26.1	31.3	36.0	40.1	43.9	47.2	50.1	52.7	55.1	57.2	59.1	60.8	62.3	63.7	64.9	66.1	67.2
	K	****	****	****	1.52	1.98	2.49	3.07	3.70	4.41	5.19	6.03	6.95	7.95	9.01	10.15	11.37	12.67	14.03	15.48	17.00
0.005	%C	****	****	****	****	98.1	94.4	90.7	87.6	85.0	82.8	81.0	79.6	78.4	77.4	76.5	75.8	75.2	74.7	74.2	73.8
	F	3.215	1.794	1.276	1.015	0.861	0.763	0.696	0.648	0.612	0.585	0.565	0.548	0.535	0.524	0.515	0.508	0.502	0.497	0.492	0.488
	A	8.0	14.5	20.7	26.3	31.5	36.1	40.3	44.0	47.3	50.2	52.8	55.2	57.3	59.1	60.8	62.3	63.7	65.0	66.1	67.2
	K	****	****	****	****	1.60	2.01	2.47	2.98	3.55	4.17	4.85	5.59	6.39	7.25	8.16	9.14	10.18	11.27	12.43	13.65
0.006	%C	****	****	****	****	****	99.2	97.2	94.9	92.9	91.1	89.5	88.2	87.1	86.2	85.4	84.7	84.2	83.6	83.2	82.8
	F	3.736	2.116	1.514	1.208	1.028	0.912	0.832	0.775	0.733	0.701	0.677	0.657	0.641	0.629	0.618	0.609	0.602	0.596	0.590	0.586
	A	8.3	14.8	20.9	26.5	31.7	36.3	40.5	44.1	47.4	50.3	52.9	55.3	57.3	59.2	60.9	62.4	63.8	65.0	66.2	67.2
	K	****	****	****	****	****	1.69	2.08	2.51	2.98	3.50	4.07	4.69	5.35	6.07	6.83	7.65	8.51	9.43	10.40	11.42
0.007	%C	****	****	****	****	****	****	99.9	99.0	97.9	96.7	95.5	94.5	93.6	92.9	92.2	91.6	91.1	90.7	90.3	89.9
	F	4.225	2.429	1.748	1.399	1.193	1.059	0.968	0.902	0.854	0.817	0.788	0.766	0.748	0.733	0.721	0.710	0.702	0.695	0.688	0.683
	A	8.6	15.0	21.1	26.8	31.9	36.5	40.6	44.3	47.6	50.5	53.0	55.3	57.4	59.3	60.9	62.5	63.8	65.1	66.2	67.3
	K	****	****	****	****	****	****	1.79	2.16	2.57	3.02	3.51	4.04	4.61	5.23	5.88	6.58	7.33	8.12	8.95	9.82
0.008	%C	****	****	****	****	****	****	****	****	99.9	99.5	99.0	98.4	97.9	97.3	96.9	96.4	96.1	95.7	95.4	95.2
	F	4.686	2.731	1.977	1.587	1.356	1.206	1.102	1.029	0.974	0.932	0.900	0.874	0.854	0.837	0.823	0.812	0.802	0.794	0.786	0.780
	A	8.8	15.3	21.4	27.0	32.1	36.7	40.8	44.4	47.7	50.6	53.1	55.4	57.5	59.3	61.0	62.5	63.9	65.1	66.3	67.3
	K	****	****	****	****	****	****	****	****	2.26	2.66	3.09	3.55	4.06	4.60	5.17	5.79	6.44	7.13	7.86	8.63
0.010	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	100.0	100.0	99.9
	F	5.530	3.308	2.420	1.956	1.677	1.495	1.370	1.279	1.213	1.162	1.122	1.091	1.065	1.045	1.028	1.013	1.001	0.991	0.982	0.975
	A	9.4	15.8	21.8	27.4	32.5	37.0	41.1	44.7	47.9	50.8	53.3	55.6	57.6	59.5	61.1	62.6	64.0	65.2	66.4	67.4
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	5.75	6.34	6.95

CARRIERS 24 PICKS 15 ENDS 4

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	97.4	71.7	57.0	49.0	44.3	41.4	39.4	38.0	37.0	36.2	35.7	35.2	34.9	34.6	34.4	34.2	34.0	33.9	33.8	33.7
	F	0.838	0.468	0.345	0.286	0.254	0.234	0.221	0.212	0.206	0.202	0.198	0.195	0.193	0.191	0.190	0.189	0.188	0.187	0.186	0.186
	A	12.4	22.6	31.5	39.0	45.2	50.2	54.4	57.9	60.8	63.3	65.4	67.2	68.8	70.2	71.4	72.5	73.4	74.3	75.1	75.8
	K	1.25	2.50	3.99	5.78	7.92	10.44	13.35	16.67	20.40	24.56	29.13	34.13	39.55	45.40	51.67	58.37	65.50	73.05	81.03	89.44
0.004	%C	******	85.2	70.3	61.5	56.1	52.6	50.2	48.6	47.4	46.5	45.8	45.3	44.8	44.5	44.2	44.0	43.8	43.6	43.5	43.4
	F	1.081	0.615	0.455	0.379	0.337	0.311	0.295	0.283	0.275	0.268	0.264	0.260	0.257	0.255	0.253	0.252	0.250	0.249	0.248	0.248
	A	12.8	23.0	31.8	39.2	45.4	50.4	54.6	58.0	60.9	63.4	65.5	67.3	68.8	70.2	71.4	72.5	73.5	74.3	75.1	75.8
	K	******	1.92	3.04	4.39	6.01	7.91	10.11	12.61	15.42	18.55	21.99	25.75	29.83	34.23	38.95	43.98	49.34	55.02	61.02	67.34
0.005	%C	******	94.1	81.0	72.1	66.4	62.6	60.0	58.2	56.8	55.8	55.1	54.4	54.0	53.6	53.3	53.0	52.8	52.6	52.4	52.3
	F	1.308	0.757	0.564	0.472	0.420	0.388	0.367	0.353	0.343	0.335	0.330	0.325	0.322	0.319	0.316	0.314	0.313	0.312	0.310	0.309
	A	13.3	23.4	32.1	39.5	45.6	50.6	54.7	58.2	61.0	63.5	65.5	67.3	68.9	70.3	71.5	72.5	73.5	74.4	75.1	75.8
	K	******	1.57	2.47	3.56	4.86	6.39	8.16	10.17	12.43	14.94	17.71	20.73	24.00	27.53	31.31	35.35	39.65	44.20	49.01	54.08
0.006	%C	******	98.9	89.2	80.9	75.2	71.3	68.7	66.7	65.3	64.2	63.4	62.8	62.3	61.8	61.5	61.2	61.0	60.8	60.6	60.5
	F	1.522	0.894	0.671	0.563	0.502	0.465	0.440	0.423	0.411	0.402	0.395	0.390	0.386	0.382	0.380	0.377	0.375	0.374	0.372	0.371
	A	13.7	23.7	32.5	39.8	45.8	50.8	54.9	58.3	61.1	63.6	65.6	67.4	69.0	70.3	71.5	72.6	73.5	74.4	75.2	75.9
	K	******	1.33	2.09	3.01	4.10	5.38	6.86	8.55	10.44	12.54	14.85	17.38	20.11	23.06	26.23	29.60	33.19	36.99	41.01	45.24
0.007	%C	******	******	95.0	87.9	82.7	78.9	76.2	74.3	72.9	71.8	70.9	70.3	69.7	69.3	68.9	68.6	68.4	68.2	68.0	67.9
	F	1.723	1.028	0.776	0.653	0.584	0.541	0.513	0.493	0.479	0.469	0.461	0.455	0.450	0.446	0.443	0.440	0.438	0.436	0.434	0.433
	A	14.1	24.1	32.8	40.0	46.0	51.0	55.0	58.4	61.2	63.6	65.7	67.5	69.0	70.4	71.6	72.6	73.6	74.4	75.2	75.9
	K	******	******	1.82	2.61	3.56	4.66	5.94	7.39	9.02	10.83	12.81	14.99	17.34	19.87	22.59	25.49	28.57	31.84	35.29	38.92
0.008	%C	******	******	98.5	93.3	88.7	85.3	82.8	80.9	79.5	78.4	77.6	76.9	76.4	75.9	75.6	75.3	75.0	74.8	74.6	74.5
	F	1.913	1.158	0.879	0.742	0.664	0.616	0.585	0.563	0.547	0.535	0.526	0.519	0.514	0.509	0.506	0.503	0.500	0.498	0.496	0.495
	A	14.5	24.5	33.1	40.3	46.2	51.1	55.2	58.5	61.3	63.7	65.8	67.5	69.1	70.4	71.6	72.7	73.6	74.5	75.2	75.9
	K	******	******	1.62	2.32	3.15	4.12	5.24	6.52	7.95	9.54	11.29	13.19	15.26	17.48	19.87	22.41	25.11	27.98	31.00	34.19
0.010	%C	******	******	******	99.3	96.9	94.6	92.6	91.1	89.9	89.0	88.2	87.7	87.2	86.8	86.5	86.2	86.0	85.8	85.6	85.4
	F	2.264	1.408	1.081	0.918	0.825	0.767	0.728	0.702	0.682	0.668	0.657	0.649	0.642	0.636	0.632	0.628	0.625	0.623	0.620	0.618
	A	15.4	25.2	33.7	40.8	46.7	51.5	55.5	58.8	61.6	63.9	65.9	67.7	69.2	70.5	71.7	72.7	73.7	74.5	75.3	76.0
	K	******	******	******	1.90	2.58	3.36	4.27	5.30	6.46	7.74	9.15	10.68	12.34	14.13	16.05	18.10	20.27	22.57	25.00	27.56

		CARRIERS 24	PICKS 15	ENDS 7																	
STR.DIA.		DIAMETER OVER DIELECTRYC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	96.7	84.2	75.1	69.1	65.2	62.5	60.5	59.1	58.1	57.3	56.7	56.2	55.8	55.4	55.2	54.9	54.7	54.6	54.4
	F	1.467	0.820	0.603	0.501	0.444	0.410	0.387	0.372	0.361	0.353	0.346	0.342	0.338	0.335	0.332	0.330	0.329	0.327	0.326	0.325
	A	12.4	22.6	31.5	39.0	45.2	50.2	54.4	57.9	60.8	63.3	65.4	67.2	68.8	70.2	71.4	72.5	73.4	74.3	75.1	75.8
	K	******	1.43	2.28	3.30	4.53	5.96	7.63	9.53	11.66	14.03	16.65	19.50	22.60	25.94	29.52	33.35	37.43	41.74	46.30	51.11
0.004	%C	******	******	95.9	88.7	83.2	79.3	76.5	74.5	73.0	71.9	71.0	70.3	69.8	69.3	69.0	68.7	68.4	68.2	68.0	67.9
	F	1.891	1.076	0.797	0.664	0.590	0.545	0.515	0.495	0.481	0.470	0.462	0.455	0.450	0.446	0.443	0.440	0.438	0.436	0.435	0.433
	A	12.8	23.0	31.8	39.2	45.4	50.4	54.6	58.0	60.9	63.4	65.5	67.3	68.8	70.2	71.4	72.5	73.5	74.3	75.1	75.8
	K	******	******	1.74	2.51	3.43	4.52	5.77	7.20	8.81	10.60	12.57	14.72	17.05	19.56	22.26	25.13	28.20	31.44	34.87	38.48
0.005	%C	******	******	100.0	96.9	93.0	89.7	87.3	85.4	84.0	82.9	82.1	81.4	80.9	80.4	80.1	79.8	79.5	79.3	79.1	79.0
	F	2.289	1.324	0.987	0.825	0.735	0.679	0.643	0.618	0.600	0.587	0.577	0.569	0.563	0.558	0.554	0.550	0.548	0.545	0.543	0.541
	A	13.3	23.4	32.1	39.5	45.6	50.6	54.7	58.2	61.0	63.5	65.5	67.3	68.9	70.3	71.5	72.5	73.5	74.4	75.1	75.8
	K	******	******	1.41	2.04	2.78	3.65	4.66	5.81	7.10	8.54	10.12	11.84	13.71	15.73	17.89	20.20	22.66	25.26	28.01	30.90
0.006	%C	******	******	******	100.0	98.5	96.5	94.7	93.3	92.1	91.2	90.5	89.9	89.4	89.0	88.7	88.5	88.2	88.0	87.9	87.7
	F	2.663	1.565	1.174	0.985	0.879	0.813	0.770	0.741	0.719	0.704	0.692	0.682	0.675	0.669	0.664	0.660	0.657	0.654	0.652	0.650
	A	13.7	23.7	32.5	39.8	45.8	50.8	54.9	58.3	61.1	63.6	65.6	67.4	69.0	70.3	71.5	72.6	73.5	74.4	75.2	75.9
	K	******	******	******	1.72	2.34	3.08	3.92	4.88	5.97	7.17	8.49	9.93	11.49	13.18	14.99	16.91	18.97	21.14	23.43	25.85
0.007	%C	******	******	******	******	******	99.7	98.9	98.1	97.4	96.8	96.3	95.8	95.5	95.2	94.9	94.7	94.5	94.4	94.3	94.1
	F	3.015	1.799	1.357	1.142	1.021	0.946	0.897	0.863	0.838	0.820	0.806	0.796	0.787	0.780	0.775	0.770	0.766	0.763	0.760	0.758
	A	14.1	24.1	32.8	40.0	46.0	51.0	55.0	58.4	61.2	63.6	65.7	67.5	69.0	70.4	71.6	72.6	73.6	74.4	75.2	75.9
	K	******	******	******	******	******	2.66	3.39	4.22	5.15	6.19	7.32	8.56	9.91	11.36	12.91	14.57	16.33	18.20	20.17	22.24
0.008	%C	******	******	******	******	******	******	******	100.0	99.8	99.6	99.4	99.2	99.0	98.8	98.7	98.6	98.5	98.4	98.3	98.2
	F	3.348	2.026	1.538	1.299	1.163	1.079	1.023	0.985	0.957	0.937	0.921	0.909	0.899	0.892	0.885	0.880	0.876	0.872	0.869	0.866
	A	14.5	24.5	33.1	40.3	46.2	51.1	55.2	58.5	61.3	63.7	65.8	67.5	69.1	70.4	71.6	72.7	73.6	74.5	75.2	75.9
	K	******	******	******	******	******	******	******	3.73	4.54	5.45	6.45	7.54	8.72	9.99	11.35	12.81	14.35	15.99	17.72	19.54
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	3.961	2.463	1.891	1.606	1.443	1.342	1.275	1.228	1.194	1.169	1.150	1.135	1.123	1.114	1.106	1.099	1.094	1.089	1.086	1.082
	A	15.4	25.2	33.7	40.8	46.7	51.5	55.5	58.8	61.6	63.9	65.9	67.7	69.2	70.5	71.7	72.7	73.7	74.5	75.3	76.0
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

	CARRIERS 24	PICKS 15	ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	******	98.1	91.9	86.7	82.8	80.0	78.0	76.5	75.4	74.5	73.8	73.2	72.8	72.4	72.1	71.9	71.6	71.5	71.3
	F	2.095	1.171	0.861	0.715	0.635	0.585	0.553	0.531	0.515	0.504	0.495	0.488	0.483	0.478	0.475	0.472	0.469	0.467	0.466	0.464
	A	12.4	22.6	31.5	39.0	45.2	50.2	54.4	57.9	60.8	63.3	65.4	67.2	68.8	70.2	71.4	72.5	73.4	74.3	75.1	75.8
	K	******	******	1.60	2.31	3.17	4.17	5.34	6.67	8.16	9.82	11.65	13.65	15.82	18.16	20.67	23.35	26.20	29.22	32.41	35.78
0.004	%C	******	******	******	99.7	97.5	95.1	93.0	91.4	90.2	89.2	88.4	87.8	87.3	86.9	86.5	86.2	86.0	85.8	85.6	85.5
	F	2.702	1.537	1.138	0.948	0.843	0.779	0.736	0.707	0.687	0.671	0.660	0.651	0.643	0.638	0.633	0.629	0.626	0.623	0.621	0.619
	A	12.8	23.0	31.8	39.2	45.4	50.4	54.6	58.0	60.9	63.4	65.5	67.3	68.8	70.2	71.4	72.5	73.5	74.3	75.1	75.8
	K	******	******	******	1.76	2.40	3.16	4.04	5.04	6.17	7.42	8.80	10.30	11.93	13.69	15.58	17.59	19.74	22.01	24.41	26.94
0.005	%C	******	******	******	******	******	99.9	99.3	98.6	98.0	97.4	96.9	96.5	96.2	95.9	95.6	95.4	95.3	95.1	95.0	94.9
	F	3.270	1.891	1.410	1.179	1.050	0.971	0.919	0.883	0.857	0.838	0.824	0.813	0.804	0.797	0.791	0.786	0.782	0.779	0.776	0.773
	A	13.3	23.4	32.1	39.5	45.6	50.6	54.7	58.2	61.0	63.5	65.5	67.3	68.9	70.3	71.5	72.5	73.5	74.4	75.1	75.8
	K	******	******	******	******	******	2.56	3.26	4.07	4.97	5.98	7.08	8.29	9.60	11.01	12.53	14.14	15.86	17.68	19.60	21.63
0.006	%C	******	******	******	******	******	******	******	******	******	******	100.0	99.9	99.9	99.8	99.7	99.7	99.6	99.6	99.5	99.5
	F	3.804	2.235	1.677	1.407	1.255	1.162	1.100	1.058	1.028	1.005	0.988	0.975	0.964	0.956	0.949	0.943	0.938	0.934	0.931	0.928
	A	13.7	23.7	32.5	39.8	45.8	50.8	54.9	58.3	61.1	63.6	65.6	67.4	69.0	70.3	71.5	72.6	73.5	74.4	75.2	75.9
	K	******	******	******	******	******	******	******	******	******	******	5.94	6.95	8.05	9.23	10.49	11.84	13.28	14.80	16.40	18.10
0.007	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	4.308	2.570	1.939	1.632	1.459	1.352	1.281	1.233	1.198	1.172	1.152	1.137	1.125	1.115	1.107	1.100	1.095	1.090	1.086	1.083
	A	14.1	24.1	32.8	40.0	46.0	51.0	55.0	58.4	61.2	63.6	65.7	67.5	69.0	70.4	71.6	72.6	73.6	74.4	75.2	75.9
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.008	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	4.783	2.895	2.197	1.855	1.661	1.541	1.462	1.407	1.367	1.338	1.316	1.298	1.285	1.274	1.265	1.257	1.251	1.246	1.241	1.237
	A	14.5	24.5	33.1	40.3	46.2	51.1	55.2	58.5	61.3	63.7	65.8	67.5	69.1	70.4	71.6	72.7	73.6	74.5	75.2	75.9
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	5.659	3.519	2.702	2.294	2.062	1.917	1.821	1.754	1.706	1.670	1.643	1.622	1.605	1.591	1.580	1.571	1.563	1.556	1.551	1.546
	A	15.4	25.2	33.7	40.8	46.7	51.5	55.5	58.8	61.6	63.9	65.9	67.7	69.2	70.5	71.7	72.7	73.7	74.5	75.3	76.0
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

CARRIERS 36 PICKS 3 ENDS 4

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	87.7	68.9	55.9	46.9	40.3	35.4	31.6	28.6	26.1	24.1	22.4	20.9	19.7	18.6	17.7	16.8	16.1	15.4	14.9
	F	1.228	0.650	0.442	0.336	0.271	0.228	0.196	0.173	0.155	0.141	0.129	0.119	0.111	0.104	0.098	0.093	0.088	0.084	0.080	0.077
	A	1.7	3.2	4.7	6.2	7.6	9.1	10.6	12.0	13.4	14.8	16.2	17.6	19.0	20.3	21.6	22.9	24.1	25.4	26.6	27.8
	K	******	1.54	2.28	3.01	3.76	4.51	5.27	6.04	6.82	7.61	8.42	9.25	10.09	10.95	11.83	12.72	13.64	14.58	15.55	16.54
0.004	%C	******	97.8	82.5	69.0	58.9	51.2	45.3	40.7	36.9	33.9	31.3	29.1	27.3	25.7	24.3	23.1	22.1	21.1	20.3	19.5
	F	1.581	0.850	0.582	0.443	0.359	0.301	0.261	0.230	0.206	0.187	0.171	0.158	0.147	0.138	0.130	0.123	0.117	0.112	0.107	0.103
	A	1.7	3.2	4.7	6.2	7.7	9.2	10.6	12.1	13.5	14.9	16.3	17.7	19.0	20.3	21.6	22.9	24.2	25.4	26.6	27.8
	K	******	1.18	1.73	2.28	2.84	3.40	3.97	4.55	5.14	5.73	6.34	6.96	7.59	8.24	8.90	9.57	10.26	10.97	11.69	12.43
0.005	%C	******	******	92.1	79.7	69.2	60.9	54.3	49.0	44.7	41.1	38.1	35.6	33.4	31.5	29.8	28.4	27.1	26.0	24.9	24.0
	F	1.911	1.043	0.719	0.549	0.445	0.374	0.324	0.286	0.256	0.233	0.213	0.197	0.184	0.172	0.162	0.154	0.146	0.139	0.134	0.128
	A	1.8	3.3	4.8	6.3	7.8	9.2	10.7	12.1	13.5	15.0	16.3	17.7	19.1	20.4	21.7	23.0	24.2	25.5	26.7	27.9
	K	******	******	1.40	1.84	2.29	2.74	3.20	3.66	4.13	4.61	5.09	5.59	6.09	6.61	7.14	7.68	8.23	8.80	9.38	9.97
0.006	%C	******	******	97.8	87.9	77.9	69.4	62.4	56.6	51.9	47.9	44.5	41.6	39.1	37.0	35.1	33.4	31.9	30.6	29.4	28.4
	F	2.219	1.230	0.852	0.653	0.530	0.447	0.387	0.341	0.306	0.278	0.255	0.236	0.220	0.206	0.194	0.184	0.175	0.167	0.160	0.154
	A	1.9	3.4	4.8	6.3	7.8	9.3	10.7	12.2	13.6	15.0	16.4	17.8	19.1	20.4	21.8	23.0	24.3	25.5	26.7	27.9
	K	******	******	1.18	1.55	1.92	2.30	2.68	3.07	3.46	3.85	4.26	4.67	5.10	5.53	5.97	6.42	6.88	7.35	7.83	8.33
0.007	%C	******	******	100.0	94.0	85.1	76.7	69.6	63.6	58.5	54.2	50.5	47.4	44.6	42.2	40.1	38.3	36.6	35.1	33.8	32.6
	F	2.508	1.410	0.982	0.754	0.613	0.518	0.449	0.397	0.356	0.323	0.297	0.274	0.256	0.240	0.226	0.214	0.204	0.195	0.186	0.179
	A	1.9	3.4	4.9	6.4	7.9	9.3	10.8	12.2	13.7	15.1	16.5	17.8	19.2	20.5	21.8	23.1	24.3	25.6	26.8	28.0
	K	******	******	1.03	1.34	1.66	1.98	2.31	2.64	2.98	3.32	3.67	4.02	4.38	4.75	5.13	5.52	5.91	6.32	6.73	7.16
0.008	%C	******	******	******	97.9	90.8	83.0	76.0	69.9	64.6	60.1	56.2	52.8	49.8	47.2	44.9	42.9	41.1	39.5	38.0	36.7
	F	2.780	1.583	1.109	0.854	0.696	0.588	0.510	0.451	0.405	0.368	0.338	0.313	0.292	0.273	0.258	0.244	0.232	0.222	0.213	0.204
	A	2.0	3.5	5.0	6.5	7.9	9.4	10.8	12.3	13.7	15.1	16.5	17.9	19.2	20.6	21.9	23.1	24.4	25.6	26.8	28.0
	K	******	******	******	1.19	1.46	1.75	2.03	2.32	2.62	2.92	3.22	3.53	3.85	4.17	4.50	4.84	5.19	5.54	5.90	6.28
0.010	%C	******	******	******	******	98.0	92.5	86.4	80.5	75.2	70.5	66.3	62.6	59.4	56.5	53.9	51.6	49.5	47.7	46.0	44.5
	F	3.276	1.914	1.353	1.049	0.857	0.726	0.631	0.559	0.502	0.457	0.420	0.389	0.363	0.340	0.321	0.304	0.289	0.277	0.265	0.255
	A	2.1	3.6	5.1	6.6	8.0	9.5	11.0	12.4	13.8	15.2	16.6	18.0	19.3	20.7	22.0	23.2	24.5	25.7	26.9	28.1
	K	******	******	******	******	1.19	1.42	1.64	1.88	2.11	2.35	2.60	2.84	3.10	3.36	3.62	3.89	4.17	4.46	4.75	5.05

CARRIERS 36 PICKS 3 ENDS 7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C************			94.9	83.0	72.4	63.8	56.9	51.4	46.9	43.1	40.0	37.3	35.0	33.0	31.3	29.8	28.4	27.2	26.2	25.2
	F	2.150	1.137	0.774	0.587	0.474	0.398	0.344	0.303	0.271	0.246	0.225	0.208	0.194	0.182	0.171	0.162	0.154	0.147	0.141	0.135
	A	1.7	3.2	4.7	6.2	7.6	9.1	10.6	12.0	13.4	14.8	16.2	17.6	19.0	20.3	21.6	22.9	24.1	25.4	26.6	27.8
	K************			1.30	1.72	2.15	2.58	3.01	3.45	3.90	4.35	4.81	5.28	5.76	6.26	6.76	7.27	7.80	8.33	8.89	9.45
0.004	%C******************				95.0	86.1	77.7	70.4	64.2	59.1	54.7	50.9	47.7	44.9	42.5	40.4	38.5	36.8	35.3	34.0	32.8
	F	2.767	1.488	1.019	0.776	0.627	0.528	0.456	0.402	0.360	0.327	0.300	0.277	0.258	0.242	0.228	0.216	0.205	0.196	0.187	0.180
	A	1.7	3.2	4.7	6.2	7.7	9.2	10.6	12.1	13.5	14.9	16.3	17.7	19.0	20.3	21.6	22.9	24.2	25.4	26.6	27.8
	K******************				1.30	1.62	1.94	2.27	2.60	2.94	3.28	3.62	3.98	4.34	4.71	5.08	5.47	5.86	6.27	6.68	7.10
0.005	%C******************				99.8	95.1	88.1	81.2	75.0	69.6	64.8	60.7	57.1	54.0	51.2	48.7	46.6	44.6	42.9	41.3	39.9
	F	3.344	1.826	1.258	0.961	0.778	0.655	0.567	0.500	0.448	0.407	0.373	0.345	0.321	0.301	0.284	0.269	0.256	0.244	0.234	0.225
	A	1.8	3.3	4.8	6.3	7.8	9.2	10.7	12.1	13.5	15.0	16.3	17.7	19.1	20.4	21.7	23.0	24.2	25.5	26.7	27.9
	K******************				1.05	1.31	1.57	1.83	2.09	2.36	2.63	2.91	3.19	3.48	3.78	4.08	4.39	4.70	5.03	5.36	5.70
0.006	%C************************					99.5	95.2	89.5	83.8	78.5	73.6	69.3	65.5	62.1	59.1	56.4	54.0	51.9	49.9	48.2	46.6
	F	3.883	2.152	1.491	1.142	0.927	0.782	0.677	0.598	0.536	0.487	0.446	0.413	0.385	0.361	0.340	0.322	0.306	0.292	0.280	0.269
	A	1.9	3.4	4.8	6.3	7.8	9.3	10.7	12.2	13.6	15.0	16.4	17.8	19.1	20.4	21.8	23.0	24.3	25.5	26.7	27.9
	K************************					1.10	1.31	1.53	1.75	1.98	2.20	2.43	2.67	2.91	3.16	3.41	3.67	3.93	4.20	4.48	4.76
0.007	%C******************************						99.1	95.4	90.6	85.8	81.1	76.9	73.0	69.5	66.3	63.5	60.9	58.6	56.5	54.6	52.9
	F	4.389	2.467	1.718	1.320	1.074	0.906	0.785	0.694	0.623	0.566	0.519	0.480	0.448	0.420	0.396	0.375	0.357	0.341	0.326	0.313
	A	1.9	3.4	4.9	6.4	7.9	9.3	10.8	12.2	13.7	15.1	16.5	17.8	19.2	20.5	21.8	23.1	24.3	25.6	26.8	28.0
	K******************************						1.13	1.32	1.51	1.70	1.90	2.09	2.30	2.50	2.72	2.93	3.15	3.38	3.61	3.85	4.09
0.008	%C************************************							98.8	95.6	91.5	87.3	83.3	79.5	76.0	72.8	69.9	67.2	64.8	62.6	60.6	58.7
	F	4.864	2.771	1.940	1.495	1.218	1.029	0.893	0.789	0.709	0.644	0.591	0.547	0.510	0.479	0.451	0.428	0.407	0.388	0.372	0.358
	A	2.0	3.5	5.0	6.5	7.9	9.4	10.8	12.3	13.7	15.1	16.5	17.9	19.2	20.6	21.9	23.1	24.4	25.6	26.8	28.0
	K************************************							1.16	1.33	1.49	1.67	1.84	2.02	2.20	2.38	2.57	2.77	2.96	3.17	3.37	3.59
0.010	%C**								100.0	98.5	96.0	92.9	89.8	86.6	83.6	80.8	78.1	75.7	73.4	71.2	69.3
	F	5.733	3.349	2.369	1.835	1.500	1.271	1.104	0.978	0.879	0.799	0.734	0.680	0.634	0.595	0.562	0.532	0.507	0.484	0.464	0.446
	A	2.1	3.6	5.1	6.6	8.0	9.5	11.0	12.4	13.8	15.2	16.6	18.0	19.3	20.7	22.0	23.2	24.5	25.7	26.9	28.1
	K**								1.07	1.21	1.34	1.48	1.63	1.77	1.92	2.07	2.23	2.38	2.55	2.71	2.88

	CARRIERS 36	PICKS 3	ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	******	******	97.4	89.6	81.4	74.1	67.8	62.5	57.9	54.0	50.7	47.7	45.2	42.9	40.9	39.2	37.6	36.2	34.9
	F	3.071	1.624	1.106	0.839	0.677	0.569	0.491	0.433	0.388	0.351	0.322	0.298	0.277	0.260	0.245	0.231	0.220	0.210	0.201	0.193
	A	1.7	3.2	4.7	6.2	7.6	9.1	10.6	12.0	13.4	14.8	16.2	17.6	19.0	20.3	21.6	22.9	24.1	25.4	26.6	27.8
	K	******	******	******	1.21	1.50	1.80	2.11	2.41	2.73	3.05	3.37	3.70	4.04	4.38	4.73	5.09	5.46	5.83	6.22	6.61
0.004	%C	******	******	******	******	98.9	93.9	87.8	81.9	76.4	71.6	67.3	63.5	60.1	57.1	54.5	52.1	50.0	48.1	46.4	44.8
	F	3.953	2.125	1.455	1.108	0.896	0.754	0.651	0.574	0.515	0.467	0.428	0.396	0.368	0.345	0.325	0.308	0.293	0.279	0.268	0.257
	A	1.7	3.2	4.7	6.2	7.7	9.2	10.6	12.1	13.5	14.9	16.3	17.7	19.0	20.3	21.6	22.9	24.2	25.4	26.6	27.8
	K	******	******	******	******	1.14	1.36	1.59	1.82	2.06	2.29	2.54	2.78	3.04	3.29	3.56	3.83	4.10	4.39	4.68	4.97
0.005	%C	******	******	******	******	******	99.6	96.4	91.9	87.1	82.5	78.2	74.3	70.8	67.6	64.7	62.1	59.7	57.6	55.6	53.9
	F	4.777	2.609	1.797	1.372	1.112	0.936	0.810	0.715	0.641	0.581	0.533	0.493	0.459	0.430	0.406	0.384	0.365	0.349	0.334	0.321
	A	1.8	3.3	4.8	6.3	7.8	9.2	10.7	12.1	13.5	15.0	16.3	17.7	19.1	20.4	21.7	23.0	24.2	25.5	26.7	27.9
	K	******	******	******	******	******	1.10	1.28	1.46	1.65	1.84	2.04	2.24	2.44	2.64	2.86	3.07	3.29	3.52	3.75	3.99
0.006	%C	******	******	******	******	******	******	99.9	97.9	94.5	90.7	86.9	83.2	79.7	76.5	73.6	70.8	68.4	66.1	64.0	62.1
	F	5.548	3.075	2.130	1.632	1.324	1.116	0.967	0.854	0.766	0.695	0.638	0.590	0.550	0.515	0.486	0.460	0.438	0.418	0.400	0.384
	A	1.9	3.4	4.8	6.3	7.8	9.3	10.7	12.2	13.6	15.0	16.4	17.8	19.1	20.4	21.8	23.0	24.3	25.5	26.7	27.9
	K	******	******	******	******	******	******	1.07	1.23	1.38	1.54	1.70	1.87	2.04	2.21	2.39	2.57	2.75	2.94	3.13	3.33
0.007	%C	******	******	******	******	******	******	******	100.0	98.8	96.3	93.3	90.1	87.0	84.0	81.1	78.4	75.9	73.6	71.5	69.5
	F	6.270	3.524	2.455	1.886	1.534	1.294	1.122	0.991	0.890	0.808	0.741	0.686	0.639	0.600	0.565	0.536	0.509	0.486	0.466	0.448
	A	1.9	3.4	4.9	6.4	7.9	9.3	10.8	12.2	13.7	15.1	16.5	17.8	19.2	20.5	21.8	23.1	24.3	25.6	26.8	28.0
	K	******	******	******	******	******	******	******	1.06	1.19	1.33	1.47	1.61	1.75	1.90	2.05	2.21	2.36	2.53	2.69	2.86
0.008	%C	******	******	******	******	******	******	******	******	******	99.4	97.6	95.2	92.6	90.0	87.4	84.9	82.5	80.2	78.1	76.1
	F	6.949	3.959	2.772	2.136	1.740	1.470	1.275	1.128	1.012	0.920	0.845	0.782	0.729	0.684	0.645	0.611	0.581	0.555	0.532	0.511
	A	2.0	3.5	5.0	6.5	7.9	9.4	10.8	12.3	13.7	15.1	16.5	17.9	19.2	20.6	21.9	23.1	24.4	25.6	26.8	28.0
	K	******	******	******	******	******	******	******	******	******	1.17	1.29	1.41	1.54	1.67	1.80	1.94	2.07	2.22	2.36	2.51
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	99.9	99.1	97.8	96.1	94.3	92.4	90.5	88.6	86.8
	F	8.191	4.784	3.384	2.622	2.143	1.815	1.577	1.397	1.255	1.142	1.049	0.972	0.906	0.850	0.802	0.760	0.724	0.691	0.662	0.637
	A	2.1	3.6	5.1	6.6	8.0	9.5	11.0	12.4	13.8	15.2	16.6	18.0	19.3	20.7	22.0	23.2	24.5	25.7	26.9	28.1
	K	******	******	******	******	******	******	******	******	******	******	******	1.14	1.24	1.34	1.45	1.56	1.67	1.78	1.90	2.02

CARRIERS 36 PICKS 9 ENDS 4

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	88.3	70.2	57.9	49.5	43.6	39.4	36.1	33.7	31.7	30.1	28.9	27.8	27.0	26.2	25.6	25.1	24.7	24.3	23.9
	F	1.233	0.658	0.454	0.351	0.289	0.249	0.221	0.201	0.185	0.174	0.164	0.157	0.150	0.145	0.141	0.138	0.135	0.132	0.130	0.128
	A	5.0	9.5	13.8	17.9	21.9	25.7	29.2	32.5	35.6	38.5	41.1	43.6	45.9	48.0	49.9	51.7	53.4	54.9	56.3	57.7
	K	******	1.56	2.34	3.15	4.01	4.94	5.93	7.00	8.16	9.40	10.74	12.17	13.70	15.33	17.07	18.91	20.86	22.92	25.09	27.36
0.004	%C	******	98.1	83.8	71.2	62.0	55.2	50.1	46.3	43.2	40.8	38.9	37.4	36.1	35.0	34.1	33.3	32.6	32.1	31.6	31.2
	F	1.587	0.861	0.598	0.464	0.383	0.331	0.294	0.267	0.247	0.231	0.218	0.208	0.200	0.194	0.188	0.183	0.179	0.176	0.173	0.170
	A	5.2	9.6	13.9	18.1	22.1	25.8	29.4	32.7	35.7	38.6	41.2	43.7	45.9	48.0	50.0	51.8	53.4	55.0	56.4	57.7
	K	******	1.19	1.78	2.39	3.04	3.73	4.48	5.29	6.15	7.09	8.09	9.17	10.32	11.55	12.86	14.24	15.71	17.25	18.88	20.59
0.005	%C	******	******	93.2	81.9	72.6	65.3	59.8	55.4	52.0	49.3	47.1	45.3	43.8	42.5	41.4	40.5	39.8	39.1	38.5	38.0
	F	1.918	1.057	0.738	0.575	0.476	0.411	0.366	0.332	0.307	0.288	0.273	0.260	0.250	0.242	0.235	0.229	0.224	0.220	0.216	0.213
	A	5.4	9.8	14.1	18.3	22.2	26.0	29.5	32.8	35.9	38.7	41.3	43.8	46.0	48.1	50.0	51.8	53.5	55.0	56.4	57.8
	K	******	******	1.44	1.93	2.45	3.01	3.61	4.26	4.95	5.70	6.51	7.37	8.30	9.28	10.33	11.44	12.61	13.85	15.16	16.53
0.006	%C	******	******	98.5	90.0	81.3	74.1	68.3	63.7	60.0	57.1	54.6	52.6	51.0	49.6	48.4	47.4	46.5	45.7	45.1	44.5
	F	2.228	1.247	0.876	0.684	0.568	0.491	0.437	0.398	0.368	0.345	0.326	0.312	0.300	0.290	0.281	0.274	0.269	0.263	0.259	0.255
	A	5.6	10.0	14.3	18.4	22.4	26.1	29.6	32.9	36.0	38.8	41.4	43.9	46.1	48.2	50.1	51.9	53.6	55.1	56.5	57.8
	K	******	******	1.22	1.62	2.06	2.53	3.03	3.57	4.15	4.78	5.45	6.17	6.95	7.77	8.64	9.57	10.55	11.59	12.68	13.82
0.007	%C	******	******	******	95.6	88.3	81.5	75.8	71.1	67.3	64.1	61.6	59.4	57.6	56.1	54.8	53.7	52.8	52.0	51.3	50.7
	F	2.519	1.430	1.010	0.791	0.658	0.570	0.508	0.462	0.428	0.401	0.380	0.363	0.349	0.338	0.328	0.320	0.313	0.307	0.302	0.298
	A	5.7	10.2	14.4	18.6	22.5	26.3	29.8	33.0	36.1	38.9	41.5	44.0	46.2	48.3	50.2	52.0	53.6	55.1	56.6	57.9
	K	******	******	******	1.41	1.78	2.18	2.61	3.08	3.58	4.12	4.70	5.32	5.98	6.69	7.44	8.24	9.08	9.97	10.90	11.89
0.008	%C	******	******	******	98.9	93.6	87.6	82.2	77.6	73.7	70.6	67.9	65.7	63.8	62.2	60.9	59.7	58.7	57.8	57.1	56.4
	F	2.793	1.607	1.141	0.896	0.747	0.648	0.578	0.526	0.488	0.457	0.433	0.414	0.398	0.385	0.374	0.365	0.357	0.351	0.345	0.340
	A	5.9	10.3	14.6	18.7	22.7	26.4	29.9	33.2	36.2	39.0	41.6	44.1	46.3	48.4	50.3	52.0	53.7	55.2	56.6	57.9
	K	******	******	******	1.24	1.57	1.92	2.30	2.71	3.15	3.62	4.13	4.68	5.26	5.88	6.54	7.24	7.97	8.75	9.57	10.44
0.010	%C	******	******	******	******	99.4	96.1	92.0	88.0	84.5	81.4	78.8	76.6	74.7	73.0	71.6	70.4	69.3	68.4	67.6	66.9
	F	3.294	1.943	1.395	1.102	0.922	0.802	0.716	0.654	0.606	0.569	0.540	0.516	0.497	0.481	0.467	0.456	0.446	0.438	0.431	0.424
	A	6.3	10.7	15.0	19.1	23.0	26.7	30.2	33.4	36.4	39.2	41.8	44.2	46.5	48.5	50.4	52.2	53.8	55.3	56.7	58.0
	K	******	******	******	******	1.28	1.56	1.87	2.20	2.55	2.93	3.34	3.78	4.24	4.74	5.27	5.83	6.43	7.05	7.71	8.41

CARRIERS 36 PICKS 9 ENDS 7

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	******	95.8	85.1	75.7	68.2	62.5	57.9	54.4	51.5	49.2	47.3	45.7	44.4	43.3	42.4	41.6	40.9	40.3	39.7
	F	2.157	1.151	0.794	0.614	0.507	0.436	0.387	0.351	0.325	0.304	0.287	0.274	0.263	0.254	0.247	0.241	0.236	0.231	0.227	0.224
	A	5.0	9.5	13.8	17.9	21.9	25.7	29.2	32.5	35.6	38.5	41.1	43.6	45.9	48.0	49.9	51.7	53.4	54.9	56.3	57.7
	K	******	******	1.33	1.80	2.29	2.82	3.39	4.00	4.66	5.37	6.14	6.95	7.83	8.76	9.75	10.81	11.92	13.10	14.33	15.64
0.004	%C	******	******	******	96.4	89.2	82.2	76.4	71.6	67.7	64.5	61.8	59.7	57.8	56.3	55.0	53.9	52.9	52.1	51.4	50.7
	F	2.777	1.507	1.046	0.811	0.671	0.579	0.514	0.467	0.432	0.404	0.382	0.365	0.351	0.339	0.329	0.321	0.314	0.308	0.303	0.298
	A	5.2	9.6	13.9	18.1	22.1	25.8	29.4	32.7	35.7	38.6	41.2	43.7	45.9	48.0	50.0	51.8	53.4	55.0	56.4	57.7
	K	******	******	******	1.36	1.74	2.13	2.56	3.02	3.52	4.05	4.63	5.24	5.90	6.60	7.35	8.14	8.98	9.86	10.79	11.77
0.005	%C	******	******	******	******	97.2	92.1	87.0	82.5	78.6	75.4	72.6	70.3	68.4	66.7	65.3	64.1	63.0	62.1	61.3	60.6
	F	3.357	1.850	1.292	1.006	0.833	0.720	0.640	0.582	0.538	0.504	0.477	0.455	0.438	0.423	0.411	0.401	0.392	0.384	0.378	0.372
	A	5.4	9.8	14.1	18.3	22.2	26.0	29.5	32.8	35.9	38.7	41.3	43.8	46.0	48.1	50.0	51.8	53.5	55.0	56.4	57.8
	K	******	******	******	******	1.40	1.72	2.06	2.43	2.83	3.26	3.72	4.21	4.74	5.30	5.90	6.54	7.21	7.92	8.66	9.45
0.006	%C	******	******	******	******	100.0	98.0	94.5	90.7	87.3	84.3	81.6	79.3	77.4	75.7	74.3	73.0	71.9	70.9	70.1	69.4
	F	3.900	2.182	1.533	1.196	0.993	0.859	0.765	0.696	0.644	0.603	0.571	0.545	0.524	0.507	0.493	0.480	0.470	0.461	0.453	0.447
	A	5.6	10.0	14.3	18.4	22.4	26.1	29.6	32.9	36.0	38.8	41.4	43.9	46.1	48.2	50.1	51.9	53.6	55.1	56.5	57.8
	K	******	******	******	******	1.18	1.44	1.73	2.04	2.37	2.73	3.12	3.53	3.97	4.44	4.94	5.47	6.03	6.62	7.24	7.90
0.007	%C	******	******	******	******	******	100.0	98.8	96.3	93.7	91.1	88.8	86.7	84.9	83.3	81.9	80.6	79.6	78.6	77.8	77.0
	F	4.409	2.502	1.768	1.384	1.151	0.997	0.888	0.809	0.749	0.702	0.665	0.635	0.611	0.591	0.574	0.560	0.548	0.537	0.528	0.521
	A	5.7	10.2	14.4	18.6	22.5	26.3	29.8	33.0	36.1	38.9	41.5	44.0	46.2	48.3	50.2	52.0	53.6	55.1	56.6	57.9
	K	******	******	******	******	******	1.25	1.49	1.76	2.05	2.35	2.68	3.04	3.42	3.82	4.25	4.71	5.19	5.70	6.23	6.79
0.008	%C	******	******	******	******	******	******	******	99.4	97.8	96.0	94.2	92.4	90.8	89.4	88.1	87.0	86.0	85.1	84.3	83.6
	F	4.888	2.812	1.997	1.569	1.307	1.134	1.011	0.921	0.853	0.800	0.759	0.725	0.697	0.674	0.655	0.639	0.626	0.614	0.604	0.595
	A	5.9	10.3	14.6	18.7	22.7	26.4	29.9	33.2	36.2	39.0	41.6	44.1	46.3	48.4	50.3	52.0	53.7	55.2	56.6	57.9
	K	******	******	******	******	******	******	******	1.55	1.80	2.07	2.36	2.67	3.00	3.36	3.74	4.13	4.56	5.00	5.47	5.96
0.010	%C	******	******	******	******	******	******	******	******	******	100.0	99.7	99.1	98.3	97.5	96.7	95.9	95.2	94.5	93.9	93.4
	F	5.764	3.401	2.442	1.929	1.614	1.403	1.254	1.144	1.061	0.996	0.944	0.903	0.869	0.841	0.817	0.798	0.781	0.766	0.754	0.743
	A	6.3	10.7	15.0	19.1	23.0	26.7	30.2	33.4	36.4	39.2	41.8	44.2	46.5	48.5	50.4	52.2	53.8	55.3	56.7	58.0
	K	******	******	******	******	******	******	******	******	******	1.67	1.91	2.16	2.43	2.71	3.01	3.33	3.67	4.03	4.41	4.80

CARRIERS 36 PICKS 9 ENDS 10

STR.DIA.		DIAMETER OVER DIELECTRIC																			
		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	****	****	****	98.5	92.4	85.8	80.0	75.2	71.2	68.0	65.2	63.0	61.1	59.5	58.1	57.0	56.0	55.1	54.4	53.7
	F	3.081	1.644	1.134	0.877	0.724	0.623	0.553	0.502	0.464	0.434	0.410	0.392	0.376	0.364	0.353	0.344	0.336	0.330	0.324	0.320
	A	5.0	9.5	13.8	17.9	21.9	25.7	29.2	32.5	35.6	38.5	41.1	43.6	45.9	48.0	49.9	51.7	53.4	54.9	56.3	57.7
	K	****	****	****	1.26	1.61	1.98	2.37	2.80	3.26	3.76	4.29	4.87	5.48	6.13	6.83	7.57	8.34	9.17	10.03	10.94
0.004	%C	****	****	****	****	99.8	97.0	92.9	88.9	85.3	82.1	79.4	77.1	75.1	73.4	71.9	70.7	69.6	68.6	67.8	67.0
	F	3.968	2.152	1.495	1.159	0.958	0.827	0.734	0.667	0.616	0.577	0.546	0.521	0.501	0.484	0.470	0.458	0.448	0.440	0.432	0.426
	A	5.2	9.6	13.9	18.1	22.1	25.8	29.4	32.7	35.7	38.6	41.2	43.7	45.9	48.0	50.0	51.8	53.4	55.0	56.4	57.7
	K	****	****	****	****	1.21	1.49	1.79	2.11	2.46	2.84	3.24	3.67	4.13	4.62	5.14	5.70	6.28	6.90	7.55	8.24
0.005	%C	****	****	****	****	****	****	99.3	97.1	94.6	92.1	89.8	87.8	86.0	84.4	82.9	81.7	80.6	79.7	78.8	78.1
	F	4.796	2.643	1.846	1.436	1.190	1.028	0.914	0.831	0.768	0.720	0.681	0.650	0.625	0.604	0.587	0.572	0.560	0.549	0.540	0.532
	A	5.4	9.8	14.1	18.3	22.2	26.0	29.5	32.8	35.9	38.7	41.3	43.8	46.0	48.1	50.0	51.8	53.5	55.0	56.4	57.8
	K	****	****	****	****	****	****	1.44	1.70	1.98	2.28	2.60	2.95	3.32	3.71	4.13	4.58	5.05	5.54	6.06	6.61
0.006	%C	****	****	****	****	****	****	****	100.0	99.4	98.1	96.6	95.1	93.7	92.4	91.2	90.2	89.2	88.3	87.6	86.9
	F	5.571	3.117	2.190	1.709	1.419	1.227	1.092	0.994	0.919	0.862	0.816	0.779	0.749	0.724	0.704	0.686	0.671	0.659	0.648	0.638
	A	5.6	10.0	14.3	18.4	22.4	26.1	29.6	32.9	36.0	38.8	41.4	43.9	46.1	48.2	50.1	51.9	53.6	55.1	56.5	57.8
	K	****	****	****	****	****	****	****	1.43	1.66	1.91	2.18	2.47	2.78	3.11	3.46	3.83	4.22	4.63	5.07	5.53
0.007	%C	****	****	****	****	****	****	****	****	****	****	99.8	99.1	98.4	97.6	96.8	96.0	95.3	94.6	94.0	93.4
	F	6.298	3.574	2.525	1.977	1.645	1.424	1.269	1.156	1.070	1.003	0.950	0.908	0.873	0.844	0.820	0.800	0.783	0.768	0.755	0.744
	A	5.7	10.2	14.4	18.6	22.5	26.3	29.8	33.0	36.1	38.9	41.5	44.0	46.2	48.3	50.2	52.0	53.6	55.1	56.6	57.9
	K	****	****	****	****	****	****	****	****	****	****	1.88	2.13	2.39	2.68	2.98	3.29	3.63	3.99	4.36	4.75
0.008	%C	****	****	****	****	****	****	****	****	****	****	****	****	100.0	99.9	99.6	99.2	98.9	98.5	98.1	97.7
	F	6.982	4.016	2.854	2.241	1.868	1.619	1.445	1.316	1.219	1.143	1.084	1.035	0.996	0.963	0.936	0.913	0.894	0.877	0.862	0.850
	A	5.9	10.3	14.6	18.7	22.7	26.4	29.9	33.2	36.2	39.0	41.6	44.1	46.3	48.4	50.3	52.0	53.7	55.2	56.6	57.9
	K	****	****	****	****	****	****	****	****	****	****	****	****	2.10	2.35	2.61	2.89	3.19	3.50	3.83	4.17
0.010	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
	F	8.234	4.859	3.488	2.755	2.305	2.004	1.791	1.634	1.515	1.423	1.349	1.290	1.241	1.201	1.168	1.139	1.115	1.094	1.077	1.061
	A	6.3	10.7	15.0	19.1	23.0	26.7	30.2	33.4	36.4	39.2	41.8	44.2	46.5	48.5	50.4	52.2	53.8	55.3	56.7	58.0
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****

CARRIERS	PICKS	ENDS
36	15	4

STR.DIA.		DIAMETER OVER DIELECTRIC 0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	*****	89.3	72.6	61.5	54.2	49.3	45.8	43.3	41.4	40.0	38.9	38.0	37.3	36.7	36.3	35.9	35.5	35.3	35.0	34.8
	F	1.241	0.673	0.476	0.379	0.323	0.288	0.264	0.247	0.235	0.226	0.218	0.213	0.208	0.205	0.202	0.199	0.197	0.195	0.194	0.193
	A	8.3	15.5	22.2	28.3	33.8	38.7	43.0	46.7	50.0	53.0	55.5	57.8	59.8	61.6	63.2	64.6	66.0	67.1	68.2	69.2
	K	*****	1.60	2.45	3.40	4.48	5.70	7.08	8.62	10.33	12.22	14.28	16.53	18.96	21.58	24.38	27.37	30.55	33.92	37.48	41.22
0.004	%C	*****	98.6	86.2	75.2	67.4	61.9	57.9	54.9	52.7	51.0	49.7	48.7	47.8	47.1	46.5	46.0	45.6	45.3	45.0	44.7
	F	1.599	0.882	0.628	0.502	0.429	0.382	0.351	0.329	0.313	0.300	0.291	0.283	0.278	0.273	0.269	0.265	0.263	0.260	0.258	0.257
	A	8.6	15.8	22.5	28.6	34.0	38.9	43.1	46.9	50.2	53.1	55.6	57.9	59.9	61.7	63.3	64.7	66.0	67.2	68.3	69.2
	K	*****	1.22	1.87	2.58	3.40	4.32	5.35	6.51	7.80	9.22	10.78	12.47	14.30	16.27	18.37	20.62	23.01	25.54	28.22	31.03
0.005	%C	*****	*****	95.0	85.8	78.2	72.5	68.3	65.2	62.8	60.9	59.4	58.3	57.3	56.5	55.9	55.3	54.9	54.5	54.2	53.9
	F	1.933	1.084	0.776	0.623	0.533	0.476	0.437	0.410	0.390	0.375	0.363	0.354	0.347	0.341	0.336	0.332	0.328	0.325	0.323	0.321
	A	8.9	16.1	22.7	28.8	34.2	39.1	43.3	47.0	50.3	53.2	55.7	57.9	59.9	61.7	63.3	64.8	66.1	67.2	68.3	69.3
	K	*****	*****	1.51	2.09	2.74	3.48	4.32	5.25	6.28	7.42	8.67	10.03	11.50	13.08	14.77	16.57	18.49	20.52	22.66	24.92
0.006	%C	*****	*****	99.4	93.3	86.8	81.4	77.3	74.1	71.6	69.7	68.1	66.9	65.9	65.0	64.3	63.7	63.2	62.8	62.5	62.2
	F	2.247	1.279	0.922	0.742	0.636	0.569	0.523	0.491	0.467	0.449	0.435	0.424	0.416	0.409	0.403	0.398	0.394	0.390	0.387	0.385
	A	9.2	16.3	23.0	29.0	34.4	39.2	43.5	47.2	50.4	53.3	55.8	58.0	60.0	61.8	63.4	64.8	66.1	67.3	68.3	69.3
	K	*****	*****	1.28	1.76	2.31	2.93	3.63	4.41	5.27	6.23	7.27	8.41	9.63	10.95	12.37	13.87	15.47	17.17	18.96	20.84
0.007	%C	*****	*****	*****	98.0	93.2	88.5	84.7	81.6	79.2	77.3	75.7	74.5	73.4	72.6	71.9	71.3	70.8	70.3	69.9	69.6
	F	2.542	1.469	1.065	0.859	0.739	0.661	0.609	0.571	0.544	0.523	0.507	0.495	0.485	0.476	0.470	0.464	0.459	0.455	0.452	0.449
	A	9.5	16.6	23.2	29.3	34.7	39.4	43.6	47.3	50.5	53.4	55.9	58.1	60.1	61.9	63.4	64.9	66.1	67.3	68.4	69.4
	K	*****	*****	*****	1.53	2.00	2.53	3.13	3.81	4.55	5.37	6.27	7.25	8.30	9.43	10.65	11.94	13.32	14.78	16.31	17.93
0.008	%C	*****	*****	*****	99.9	97.4	93.9	90.6	87.9	85.6	83.8	82.3	81.1	80.0	79.2	78.5	77.9	77.4	77.0	76.6	76.3
	F	2.819	1.652	1.204	0.975	0.840	0.753	0.694	0.652	0.621	0.597	0.579	0.565	0.553	0.544	0.536	0.530	0.525	0.520	0.516	0.513
	A	9.8	16.9	23.5	29.5	34.9	39.6	43.8	47.4	50.7	53.5	56.0	58.2	60.2	61.9	63.5	64.9	66.2	67.4	68.4	69.4
	K	*****	*****	*****	1.35	1.77	2.24	2.76	3.35	4.01	4.73	5.52	6.38	7.30	8.30	9.36	10.50	11.70	12.98	14.33	15.75
0.010	%C	*****	*****	*****	*****	*****	99.6	98.1	96.4	94.9	93.5	92.3	91.3	90.4	89.7	89.1	88.6	88.1	87.7	87.4	87.1
	F	3.329	2.002	1.476	1.202	1.039	0.934	0.862	0.811	0.773	0.744	0.722	0.705	0.691	0.679	0.670	0.662	0.655	0.650	0.645	0.641
	A	10.4	17.4	24.0	29.9	35.3	40.0	44.1	47.7	50.9	53.7	56.2	58.4	60.3	62.1	63.6	65.0	66.3	67.5	68.5	69.5
	K	*****	*****	*****	*****	*****	1.82	2.25	2.72	3.25	3.83	4.47	5.16	5.90	6.70	7.56	8.47	9.44	10.47	11.55	12.69

							CARRIERS 36		PICKS 15		ENDS 7									

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	******	97.2	88.7	81.1	75.4	71.1	67.8	65.3	63.4	61.8	60.6	59.6	58.8	58.1	57.6	57.1	56.7	56.3	56.0
	F	2.172	1.178	0.833	0.664	0.566	0.504	0.462	0.432	0.411	0.395	0.382	0.372	0.365	0.358	0.353	0.349	0.345	0.342	0.339	0.337
	A	8.3	15.5	22.2	28.3	33.8	38.7	43.0	46.7	50.0	53.0	55.5	57.8	59.8	61.6	63.2	64.6	66.0	67.1	68.2	69.2
	K	******	******	1.40	1.95	2.56	3.26	4.04	4.92	5.90	6.98	8.16	9.45	10.84	12.33	13.93	15.64	17.46	19.38	21.41	23.55
0.004	%C	******	******	******	98.5	93.8	89.1	85.1	82.0	79.5	77.5	75.9	74.6	73.5	72.7	71.9	71.3	70.8	70.4	70.0	69.7
	F	2.798	1.544	1.099	0.878	0.750	0.669	0.614	0.575	0.547	0.525	0.509	0.496	0.486	0.477	0.470	0.465	0.460	0.456	0.452	0.449
	A	8.6	15.8	22.5	28.6	34.0	38.9	43.1	46.9	50.2	53.1	55.6	57.9	59.9	61.7	63.3	64.7	66.0	67.2	68.3	69.2
	K	******	******	******	1.48	1.94	2.47	3.06	3.72	4.46	5.27	6.16	7.12	8.17	9.29	10.50	11.78	13.15	14.60	16.12	17.73
0.005	%C	******	******	******	******	99.6	97.2	94.5	92.0	89.9	88.2	86.7	85.5	84.5	83.7	83.0	82.4	81.9	81.5	81.1	80.8
	F	3.383	1.897	1.359	1.090	0.933	0.833	0.765	0.718	0.682	0.656	0.635	0.619	0.607	0.596	0.588	0.580	0.574	0.569	0.565	0.561
	A	8.9	16.1	22.7	28.8	34.2	39.1	43.3	47.0	50.3	53.2	55.7	57.9	59.9	61.7	63.3	64.8	66.1	67.2	68.3	69.3
	K	******	******	******	******	1.57	1.99	2.47	3.00	3.59	4.24	4.96	5.73	6.57	7.47	8.44	9.47	10.57	11.72	12.95	14.24
0.006	%C	******	******	******	******	******	100.0	99.3	98.0	96.7	95.4	94.3	93.4	92.6	91.9	91.3	90.8	90.3	90.0	89.6	89.3
	F	3.932	2.239	1.614	1.298	1.114	0.996	0.916	0.859	0.817	0.786	0.762	0.743	0.727	0.715	0.705	0.696	0.689	0.683	0.678	0.673
	A	9.2	16.3	23.0	29.0	34.4	39.2	43.5	47.2	50.4	53.3	55.8	58.0	60.0	61.8	63.4	64.8	66.1	67.3	68.3	69.3
	K	******	******	******	******	******	1.67	2.07	2.52	3.01	3.56	4.15	4.80	5.50	6.26	7.07	7.93	8.84	9.81	10.83	11.91
0.007	%C	******	******	******	******	******	******	******	******	99.8	99.3	98.7	98.2	97.7	97.2	96.8	96.5	96.1	95.9	95.6	95.4
	F	4.448	2.570	1.863	1.504	1.293	1.157	1.065	1.000	0.952	0.916	0.888	0.866	0.848	0.834	0.822	0.812	0.804	0.797	0.791	0.785
	A	9.5	16.6	23.2	29.3	34.7	39.4	43.6	47.3	50.5	53.4	55.9	58.1	60.1	61.9	63.4	64.9	66.1	67.3	68.4	69.4
	K	******	******	******	******	******	******	******	******	2.60	3.07	3.58	4.14	4.74	5.39	6.09	6.83	7.61	8.44	9.32	10.25
0.008	%C	******	******	******	******	******	******	******	******	******	******	******	100.0	99.9	99.8	99.6	99.5	99.3	99.2	99.1	98.9
	F	4.933	2.891	2.108	1.707	1.470	1.318	1.214	1.140	1.086	1.045	1.013	0.988	0.968	0.952	0.939	0.927	0.918	0.910	0.903	0.897
	A	9.8	16.9	23.5	29.5	34.9	39.6	43.8	47.4	50.7	53.5	56.0	58.2	60.2	61.9	63.5	64.9	66.2	67.4	68.4	69.4
	K	******	******	******	******	******	******	******	******	******	******	******	3.64	4.17	4.74	5.35	6.00	6.69	7.42	8.19	9.00
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	5.825	3.503	2.582	2.104	1.819	1.635	1.509	1.419	1.353	1.303	1.264	1.233	1.209	1.189	1.172	1.158	1.147	1.137	1.128	1.121
	A	10.4	17.4	24.0	29.9	35.3	40.0	44.1	47.7	50.9	53.7	56.2	58.4	60.3	62.1	63.6	65.0	66.3	67.5	68.5	69.5
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

CARRIERS	PICKS	ENDS
36	15	10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	******	******	99.7	96.3	92.1	88.4	85.4	82.9	81.0	79.4	78.1	77.0	76.2	75.4	74.8	74.3	73.8	73.4	73.1
	F	3.102	1.683	1.190	0.948	0.808	0.720	0.660	0.618	0.587	0.564	0.546	0.532	0.521	0.512	0.504	0.498	0.493	0.488	0.485	0.481
	A	8.3	15.5	22.2	28.3	33.8	38.7	43.0	46.7	50.0	53.0	55.5	57.8	59.8	61.6	63.2	64.6	66.0	67.1	68.2	69.2
	K	******	******	******	1.36	1.79	2.28	2.83	3.45	4.13	4.89	5.71	6.61	7.58	8.63	9.75	10.95	12.22	13.57	14.99	16.49
0.004	%C	******	******	******	******	******	99.8	98.5	96.8	95.2	93.8	92.6	91.5	90.6	89.9	89.2	88.7	88.2	87.8	87.5	87.2
	F	3.997	2.205	1.570	1.255	1.072	0.956	0.877	0.822	0.781	0.751	0.727	0.709	0.694	0.682	0.672	0.664	0.657	0.651	0.646	0.642
	A	8.6	15.8	22.5	28.6	34.0	38.9	43.1	46.9	50.2	53.1	55.6	57.9	59.9	61.7	63.3	64.7	66.0	67.2	68.3	69.2
	K	******	******	******	******	******	1.73	2.14	2.60	3.12	3.69	4.31	4.99	5.72	6.51	7.35	8.25	9.21	10.22	11.29	12.41
0.005	%C	******	******	******	******	******	******	******	******	99.9	99.6	99.2	98.7	98.2	97.8	97.4	97.1	96.8	96.5	96.3	96.1
	F	4.833	2.710	1.941	1.557	1.333	1.190	1.094	1.025	0.975	0.937	0.908	0.885	0.867	0.852	0.839	0.829	0.821	0.813	0.807	0.802
	A	8.9	16.1	22.7	28.8	34.2	39.1	43.3	47.0	50.3	53.2	55.7	57.9	59.9	61.7	63.3	64.8	66.1	67.2	68.3	69.3
	K	******	******	******	******	******	******	******	******	2.51	2.97	3.47	4.01	4.60	5.23	5.91	6.63	7.40	8.21	9.06	9.97
0.006	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	100.0	100.0	99.9	99.9	99.9
	F	5.617	3.199	2.305	1.855	1.591	1.423	1.308	1.227	1.168	1.123	1.088	1.061	1.039	1.021	1.007	0.995	0.984	0.976	0.968	0.962
	A	9.2	16.3	23.0	29.0	34.4	39.2	43.5	47.2	50.4	53.3	55.8	58.0	60.0	61.8	63.4	64.8	66.1	67.3	68.3	69.3
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	5.55	6.19	6.87	7.58	8.34
0.007	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	6.354	3.672	2.661	2.148	1.847	1.653	1.522	1.429	1.360	1.308	1.268	1.237	1.211	1.191	1.174	1.160	1.148	1.138	1.129	1.122
	A	9.5	16.6	23.2	29.3	34.7	39.4	43.6	47.3	50.5	53.4	55.9	58.1	60.1	61.9	63.4	64.9	66.1	67.3	68.4	69.4
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.008	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	7.048	4.130	3.011	2.438	2.100	1.883	1.734	1.629	1.552	1.493	1.448	1.412	1.383	1.360	1.341	1.325	1.312	1.300	1.290	1.282
	A	9.8	16.9	23.5	29.5	34.9	39.6	43.8	47.4	50.7	53.5	56.0	58.2	60.2	61.9	63.5	64.9	66.2	67.4	68.4	69.4
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.010	%C	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
	F	8.321	5.005	3.689	3.005	2.599	2.336	2.156	2.028	1.933	1.861	1.806	1.762	1.727	1.698	1.674	1.655	1.638	1.624	1.612	1.602
	A	10.4	17.4	24.0	29.9	35.3	40.0	44.1	47.7	50.9	53.7	56.2	58.4	60.3	62.1	63.6	65.0	66.3	67.5	68.5	69.5
	K	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******

CARRIERS	PICKS	ENDS
48	3	4

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	98.2	83.1	69.4	59.0	51.2	45.2	40.5	36.7	33.5	30.9	28.7	26.8	25.1	23.7	22.4	21.3	20.3	19.4	18.6
	F	1.637	0.866	0.589	0.446	0.360	0.302	0.260	0.229	0.204	0.185	0.169	0.156	0.144	0.135	0.126	0.119	0.113	0.107	0.102	0.098
	A	1.3	2.4	3.5	4.6	5.7	6.9	8.0	9.1	10.2	11.2	12.3	13.4	14.4	15.5	16.5	17.6	18.6	19.6	20.6	21.6
	K	******	1.16	1.70	2.25	2.81	3.36	3.92	4.48	5.05	5.63	6.21	6.80	7.39	7.99	8.60	9.22	9.85	10.49	11.14	11.80
0.004	%C	******	******	94.9	83.2	72.6	64.0	57.1	51.5	46.9	43.1	39.8	37.1	34.7	32.6	30.8	29.2	27.8	26.5	25.4	24.4
	F	2.108	1.133	0.775	0.590	0.476	0.400	0.345	0.303	0.271	0.245	0.224	0.207	0.192	0.179	0.168	0.159	0.150	0.143	0.136	0.130
	A	1.3	2.4	3.6	4.7	5.8	6.9	8.0	9.1	10.2	11.3	12.4	13.4	14.5	15.5	16.6	17.6	18.6	19.6	20.6	21.6
	K	******	******	1.30	1.71	2.12	2.54	2.96	3.38	3.81	4.24	4.67	5.11	5.56	6.01	6.47	6.94	7.41	7.89	8.37	8.87
0.005	%C	******	******	99.8	92.7	83.2	74.6	67.4	61.2	56.1	51.8	48.1	44.9	42.1	39.7	37.6	35.7	34.0	32.5	31.1	29.9
	F	2.547	1.390	0.957	0.730	0.591	0.497	0.429	0.377	0.338	0.306	0.279	0.258	0.239	0.223	0.210	0.198	0.188	0.178	0.170	0.163
	A	1.3	2.5	3.6	4.7	5.8	6.9	8.0	9.1	10.2	11.3	12.4	13.5	14.5	15.6	16.6	17.6	18.7	19.7	20.7	21.6
	K	******	******	1.05	1.38	1.71	2.04	2.38	2.72	3.06	3.40	3.75	4.11	4.46	4.82	5.19	5.56	5.94	6.32	6.71	7.11
0.006	%C	******	******	******	98.3	91.2	83.4	76.1	69.8	64.4	59.7	55.7	52.1	49.0	46.3	43.9	41.8	39.9	38.1	36.6	35.2
	F	2.958	1.639	1.134	0.868	0.703	0.592	0.512	0.451	0.403	0.365	0.334	0.308	0.286	0.267	0.251	0.237	0.225	0.214	0.204	0.195
	A	1.4	2.5	3.6	4.8	5.9	7.0	8.1	9.2	10.3	11.4	12.4	13.5	14.6	15.6	16.7	17.7	18.7	19.7	20.7	21.7
	K	******	******	******	1.16	1.44	1.71	1.99	2.28	2.56	2.85	3.14	3.43	3.73	4.03	4.34	4.65	4.96	5.28	5.61	5.94
0.007	%C	******	******	******	******	96.6	90.2	83.5	77.3	71.8	66.9	62.6	58.8	55.5	52.5	49.9	47.6	45.5	43.5	41.8	40.3
	F	3.343	1.878	1.307	1.003	0.815	0.686	0.594	0.523	0.469	0.425	0.388	0.358	0.333	0.311	0.292	0.276	0.261	0.249	0.237	0.227
	A	1.4	2.6	3.7	4.8	5.9	7.0	8.1	9.2	10.3	11.4	12.5	13.6	14.6	15.7	16.7	17.7	18.7	19.7	20.7	21.7
	K	******	******	******	******	1.24	1.48	1.72	1.96	2.20	2.45	2.70	2.95	3.21	3.47	3.73	4.00	4.27	4.54	4.82	5.10
0.008	%C	******	******	******	******	99.4	95.1	89.4	83.6	78.2	73.3	68.9	65.0	61.5	58.4	55.5	53.0	50.7	48.7	46.8	45.1
	F	3.705	2.110	1.476	1.136	0.924	0.780	0.675	0.595	0.533	0.483	0.442	0.408	0.379	0.355	0.333	0.315	0.298	0.284	0.271	0.259
	A	1.5	2.6	3.7	4.8	6.0	7.1	8.2	9.3	10.4	11.5	12.5	13.6	14.7	15.7	16.7	17.8	18.8	19.8	20.8	21.8
	K	******	******	******	******	1.09	1.30	1.51	1.72	1.94	2.15	2.37	2.59	2.82	3.04	3.27	3.51	3.74	3.98	4.23	4.47
0.010	%C	******	******	******	******	******	99.9	97.3	93.1	88.5	84.0	79.7	75.7	72.1	68.8	65.7	63.0	60.5	58.2	56.1	54.1
	F	4.367	2.549	1.802	1.394	1.138	0.962	0.835	0.737	0.661	0.600	0.549	0.507	0.472	0.441	0.415	0.391	0.371	0.353	0.337	0.323
	A	1.6	2.7	3.8	4.9	6.1	7.2	8.3	9.4	10.5	11.5	12.6	13.7	14.7	15.8	16.8	17.8	18.9	19.9	20.9	21.8
	K	******	******	******	******	******	1.06	1.22	1.39	1.56	1.74	1.91	2.09	2.27	2.45	2.63	2.82	3.01	3.20	3.40	3.60

CARRIERS	PICKS	ENDS
48	3	7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C				95.2	86.3	77.7	70.3	64.0	58.7	54.2	50.3	47.0	44.1	41.6	39.4	37.4	35.6	34.1	32.6	31.4
	F	2.865	1.515	1.030	0.781	0.630	0.528	0.455	0.400	0.357	0.323	0.295	0.272	0.253	0.236	0.221	0.209	0.198	0.188	0.179	0.171
	A	1.3	2.4	3.5	4.6	5.7	6.9	8.0	9.1	10.2	11.2	12.3	13.4	14.4	15.5	16.5	17.6	18.6	19.6	20.6	21.6
	K				1.29	1.60	1.92	2.24	2.56	2.89	3.22	3.55	3.88	4.22	4.57	4.92	5.27	5.63	5.99	6.37	6.74
0.004	%C					97.2	91.0	84.3	78.0	72.4	67.4	63.1	59.3	55.9	52.9	50.2	47.8	45.7	43.8	42.0	40.4
	F	3.689	1.982	1.356	1.032	0.833	0.700	0.603	0.531	0.475	0.429	0.392	0.362	0.336	0.314	0.294	0.278	0.263	0.250	0.239	0.228
	A	1.3	2.4	3.6	4.7	5.8	6.9	8.0	9.1	10.2	11.3	12.4	13.4	14.5	15.5	16.6	17.6	18.6	19.6	20.6	21.6
	K					1.21	1.45	1.69	1.93	2.18	2.42	2.67	2.92	3.18	3.44	3.70	3.96	4.23	4.51	4.79	5.07
0.005	%C						98.3	93.8	88.5	83.2	78.3	73.9	69.8	66.2	62.9	60.0	57.3	54.9	52.7	50.7	48.8
	F	4.458	2.433	1.674	1.278	1.034	0.869	0.750	0.661	0.591	0.535	0.489	0.451	0.419	0.391	0.367	0.346	0.328	0.312	0.298	0.285
	A	1.3	2.5	3.6	4.7	5.8	6.9	8.0	9.1	10.2	11.3	12.4	13.5	14.5	15.6	16.6	17.6	18.7	19.7	20.7	21.6
	K						1.17	1.36	1.55	1.75	1.95	2.14	2.35	2.55	2.76	2.97	3.18	3.39	3.61	3.84	4.06
0.006	%C							98.9	95.5	91.3	87.0	82.7	78.8	75.1	71.7	68.6	65.7	63.2	60.8	58.6	56.6
	F	5.177	2.868	1.985	1.519	1.231	1.036	0.895	0.789	0.706	0.639	0.585	0.539	0.501	0.468	0.440	0.415	0.393	0.374	0.357	0.341
	A	1.4	2.5	3.6	4.8	5.9	7.0	8.1	9.2	10.3	11.4	12.4	13.5	14.6	15.6	16.7	17.7	18.7	19.7	20.7	21.7
	K							1.14	1.30	1.46	1.63	1.79	1.96	2.13	2.30	2.48	2.66	2.84	3.02	3.21	3.39
0.007	%C								99.3	96.8	93.4	89.7	86.1	82.6	79.3	76.1	73.2	70.6	68.1	65.8	63.7
	F	5.851	3.287	2.287	1.755	1.426	1.201	1.039	0.916	0.820	0.743	0.680	0.627	0.583	0.544	0.512	0.483	0.458	0.435	0.415	0.397
	A	1.4	2.6	3.7	4.8	5.9	7.0	8.1	9.2	10.3	11.4	12.5	13.6	14.6	15.7	16.7	17.7	18.7	19.7	20.7	21.7
	K								1.12	1.26	1.40	1.54	1.69	1.83	1.98	2.13	2.28	2.44	2.59	2.75	2.92
0.008	%C									99.6	97.6	94.9	91.9	88.7	85.6	82.6	79.8	77.1	74.6	72.3	70.1
	F	6.484	3.692	2.583	1.988	1.617	1.364	1.181	1.042	0.933	0.846	0.774	0.715	0.664	0.621	0.583	0.551	0.522	0.496	0.474	0.453
	A	1.5	2.6	3.7	4.8	6.0	7.1	8.2	9.3	10.4	11.5	12.5	13.6	14.7	15.7	16.7	17.8	18.8	19.8	20.8	21.8
	K									1.11	1.23	1.36	1.48	1.61	1.74	1.87	2.00	2.14	2.28	2.42	2.56
0.010	%C											99.9	98.7	96.9	94.8	92.5	90.1	87.7	85.4	83.2	81.1
	F	7.642	4.461	3.153	2.440	1.992	1.684	1.460	1.290	1.157	1.050	0.961	0.888	0.825	0.772	0.726	0.685	0.650	0.618	0.590	0.565
	A	1.6	2.7	3.8	4.9	6.1	7.2	8.3	9.4	10.5	11.5	12.6	13.7	14.7	15.8	16.8	17.8	18.9	19.9	20.9	21.8
	K											1.09	1.19	1.30	1.40	1.50	1.61	1.72	1.83	1.94	2.05

CARRIERS 48 | PICKS 3 | ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	*****	*****	*****	*****	99.0	94.0	87.8	81.6	76.0	71.0	66.6	62.6	59.1	56.0	53.2	50.8	48.5	46.5	44.7	43.0
	F	4.094	2.164	1.472	1.116	0.900	0.754	0.650	0.572	0.511	0.462	0.422	0.389	0.361	0.337	0.316	0.298	0.282	0.268	0.256	0.245
	A	1.3	2.4	3.5	4.6	5.7	6.9	8.0	9.1	10.2	11.2	12.3	13.4	14.4	15.5	16.5	17.6	18.6	19.6	20.6	21.6
	K	*****	*****	*****	*****	1.12	1.34	1.57	1.79	2.02	2.25	2.48	2.72	2.96	3.20	3.44	3.69	3.94	4.20	4.46	4.72
0.004	%C	*****	*****	*****	*****	*****	100.0	98.1	94.2	89.6	85.1	80.7	76.6	72.9	69.5	66.4	63.6	61.0	58.7	56.5	54.6
	F	5.270	2.832	1.938	1.474	1.190	0.999	0.862	0.759	0.678	0.613	0.561	0.517	0.480	0.448	0.421	0.397	0.376	0.357	0.341	0.326
	A	1.3	2.4	3.6	4.7	5.8	6.9	8.0	9.1	10.2	11.3	12.4	13.4	14.5	15.5	16.6	17.6	18.6	19.6	20.6	21.6
	K	*****	*****	*****	*****	*****	1.02	1.18	1.35	1.52	1.70	1.87	2.05	2.22	2.40	2.59	2.77	2.96	3.15	3.35	3.55
0.005	%C	*****	*****	*****	*****	*****	*****	*****	99.7	97.6	94.4	90.9	87.3	83.8	80.5	77.4	74.5	71.8	69.3	67.0	64.8
	F	6.368	3.476	2.392	1.825	1.477	1.241	1.072	0.944	0.844	0.764	0.698	0.644	0.598	0.559	0.525	0.495	0.469	0.446	0.425	0.407
	A	1.3	2.5	3.6	4.7	5.8	6.9	8.0	9.1	10.2	11.3	12.4	13.5	14.5	15.6	16.6	17.6	18.7	19.7	20.7	21.6
	K	*****	*****	*****	*****	*****	*****	*****	1.09	1.22	1.36	1.50	1.64	1.78	1.93	2.08	2.23	2.38	2.53	2.69	2.84
0.006	%C	*****	*****	*****	*****	*****	*****	*****	*****	*****	99.2	97.3	94.7	91.9	89.0	86.2	83.4	80.8	78.3	75.9	73.7
	F	7.395	4.097	2.835	2.170	1.759	1.480	1.279	1.127	1.008	0.913	0.835	0.770	0.715	0.668	0.628	0.592	0.561	0.534	0.509	0.487
	A	1.4	2.5	3.6	4.8	5.9	7.0	8.1	9.2	10.3	11.4	12.4	13.5	14.6	15.6	16.7	17.7	18.7	19.7	20.7	21.7
	K	*****	*****	*****	*****	*****	*****	*****	*****	*****	1.14	1.26	1.37	1.49	1.61	1.74	1.86	1.99	2.11	2.24	2.38
0.007	%C	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	99.9	98.9	97.2	95.1	92.8	90.4	88.0	85.7	83.4	81.3
	F	8.358	4.696	3.267	2.508	2.036	1.716	1.484	1.309	1.171	1.061	0.971	0.896	0.832	0.778	0.731	0.690	0.654	0.622	0.593	0.568
	A	1.4	2.6	3.7	4.8	5.9	7.0	8.1	9.2	10.3	11.4	12.5	13.6	14.6	15.7	16.7	17.7	18.7	19.7	20.7	21.7
	K	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	1.08	1.18	1.28	1.39	1.49	1.60	1.71	1.82	1.93	2.04
0.008	%C	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	99.7	98.7	97.2	95.4	93.5	91.5	89.5	87.6
	F	9.263	5.274	3.689	2.840	2.310	1.949	1.687	1.489	1.333	1.208	1.106	1.021	0.949	0.887	0.833	0.786	0.745	0.709	0.677	0.648
	A	1.5	2.6	3.7	4.8	6.0	7.1	8.2	9.3	10.4	11.5	12.5	13.6	14.7	15.7	16.7	17.8	18.8	19.8	20.8	21.8
	K	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	1.13	1.22	1.31	1.40	1.50	1.59	1.69	1.79
0.010	%C	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	100.0	99.5	98.6	97.5	96.3
	F	10.918	6.373	4.504	3.485	2.845	2.406	2.086	1.843	1.653	1.499	1.373	1.268	1.179	1.103	1.036	0.979	0.928	0.883	0.843	0.807
	A	1.6	2.7	3.8	4.9	6.1	7.2	8.3	9.4	10.5	11.5	12.6	13.7	14.7	15.8	16.8	17.8	18.9	19.9	20.9	21.8
	K	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	1.13	1.20	1.28	1.36	1.44

	CARRIERS	PICKS	ENDS
	48	9	4

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C******		98.4	83.8	70.6	60.8	53.6	48.1	43.8	40.4	37.7	35.5	33.7	32.2	30.9	29.8	28.9	28.1	27.4	26.8	26.3
	F	1.641	0.872	0.597	0.458	0.374	0.318	0.279	0.250	0.228	0.211	0.197	0.186	0.177	0.169	0.162	0.157	0.152	0.148	0.144	0.141
	A	3.8	7.1	10.4	13.6	16.8	19.8	22.8	25.6	28.2	30.8	33.2	35.5	37.7	39.8	41.7	43.5	45.2	46.9	48.4	49.8
	K******		1.17	1.73	2.31	2.92	3.55	4.21	4.91	5.65	6.43	7.25	8.12	9.04	10.02	11.04	12.12	13.26	14.45	15.71	17.02
0.004	%C************			95.5	84.4	74.5	66.6	60.4	55.4	51.5	48.2	45.6	43.3	41.5	39.9	38.6	37.4	36.4	35.5	34.8	34.1
	F	2.112	1.141	0.787	0.605	0.495	0.422	0.371	0.332	0.303	0.280	0.262	0.247	0.235	0.225	0.216	0.209	0.203	0.197	0.192	0.188
	A	3.9	7.3	10.5	13.8	16.9	19.9	22.9	25.7	28.3	30.9	33.3	35.6	37.8	39.8	41.8	43.6	45.3	46.9	48.5	49.9
	K************			1.31	1.75	2.21	2.68	3.18	3.70	4.26	4.84	5.46	6.12	6.81	7.54	8.31	9.13	9.98	10.88	11.82	12.80
0.005	%C************			99.9	93.7	85.1	77.4	70.9	65.6	61.3	57.7	54.7	52.2	50.0	48.2	46.7	45.3	44.2	43.2	42.3	41.5
	F	2.553	1.401	0.972	0.750	0.615	0.525	0.461	0.414	0.378	0.350	0.327	0.308	0.293	0.281	0.270	0.261	0.253	0.246	0.240	0.235
	A	4.0	7.4	10.7	13.9	17.0	20.1	23.0	25.8	28.5	31.0	33.4	35.7	37.9	39.9	41.8	43.7	45.4	47.0	48.5	50.0
	K************			1.07	1.42	1.78	2.16	2.56	2.98	3.42	3.89	4.39	4.92	5.47	6.06	6.68	7.33	8.01	8.73	9.49	10.27
0.006	%C******************				98.8	92.8	86.0	79.8	74.5	70.0	66.2	62.9	60.2	57.9	55.9	54.2	52.7	51.4	50.3	49.3	48.4
	F	2.965	1.651	1.152	0.891	0.732	0.626	0.551	0.495	0.452	0.418	0.391	0.369	0.351	0.336	0.323	0.312	0.303	0.295	0.288	0.282
	A	4.2	7.5	10.8	14.0	17.2	20.2	23.1	25.9	28.6	31.1	33.5	35.8	38.0	40.0	41.9	43.7	45.4	47.1	48.6	50.0
	K******************				1.19	1.50	1.81	2.15	2.50	2.87	3.26	3.68	4.12	4.58	5.07	5.59	6.13	6.70	7.30	7.93	8.59
0.007	%C************************					97.7	92.5	87.0	81.9	77.5	73.6	70.3	67.5	65.1	63.0	61.1	59.6	58.2	57.0	55.9	54.9
	F	3.352	1.893	1.328	1.031	0.849	0.726	0.639	0.575	0.525	0.487	0.455	0.430	0.409	0.391	0.377	0.364	0.353	0.344	0.336	0.329
	A	4.3	7.6	10.9	14.2	17.3	20.3	23.2	26.0	28.7	31.2	33.6	35.9	38.0	40.1	42.0	43.8	45.5	47.1	48.6	50.1
	K************************					1.29	1.57	1.85	2.15	2.47	2.81	3.17	3.54	3.94	4.36	4.81	5.27	5.76	6.28	6.82	7.39
0.008	%C************************					99.9	97.0	92.6	88.1	83.9	80.1	76.9	74.0	71.5	69.4	67.5	65.8	64.4	63.1	62.0	61.0
	F	3.715	2.127	1.501	1.168	0.963	0.825	0.727	0.654	0.598	0.554	0.519	0.490	0.467	0.447	0.430	0.416	0.403	0.393	0.383	0.375
	A	4.4	7.8	11.1	14.3	17.4	20.4	23.3	26.1	28.8	31.3	33.7	36.0	38.1	40.1	42.1	43.9	45.6	47.2	48.7	50.1
	K************************					1.14	1.38	1.63	1.90	2.17	2.47	2.78	3.11	3.46	3.83	4.22	4.63	5.06	5.51	5.99	6.48
0.010	%C************************************							99.0	96.5	93.4	90.3	87.5	84.8	82.4	80.3	78.5	76.8	75.3	74.0	72.8	71.7
	F	4.380	2.572	1.833	1.435	1.188	1.021	0.901	0.812	0.743	0.689	0.646	0.610	0.581	0.557	0.536	0.518	0.503	0.490	0.478	0.468
	A	4.7	8.0	11.3	14.5	17.6	20.7	23.6	26.3	29.0	31.5	33.9	36.1	38.3	40.3	42.2	44.0	45.7	47.3	48.8	50.2
	K************************************							1.32	1.53	1.76	2.00	2.25	2.51	2.79	3.09	3.40	3.73	4.08	4.44	4.82	5.22

CARRIERS 48 PICKS 9 ENDS 7

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	****	****	****	96.1	88.1	80.4	73.9	68.4	63.9	60.2	57.1	54.5	52.3	50.4	48.8	47.4	46.1	45.1	44.2	43.3
	F	2.871	1.525	1.046	0.801	0.655	0.557	0.489	0.438	0.399	0.369	0.345	0.325	0.309	0.296	0.284	0.274	0.266	0.259	0.253	0.247
	A	3.8	7.1	10.4	13.6	16.8	19.8	22.8	25.6	28.2	30.8	33.2	35.5	37.7	39.8	41.7	43.5	45.2	46.9	48.4	49.8
	K	****	****	****	1.32	1.67	2.03	2.41	2.81	3.23	3.67	4.14	4.64	5.17	5.72	6.31	6.93	7.58	8.26	8.98	9.72
0.004	%C	****	****	****	****	98.2	93.2	87.6	82.5	78.0	74.1	70.7	67.8	65.3	63.2	61.4	59.7	58.3	57.1	56.0	55.0
	F	3.697	1.997	1.377	1.059	0.867	0.739	0.648	0.582	0.531	0.491	0.459	0.433	0.411	0.393	0.378	0.365	0.354	0.345	0.337	0.329
	A	3.9	7.3	10.5	13.8	16.9	19.9	22.9	25.7	28.3	30.9	33.3	35.6	37.8	39.8	41.8	43.6	45.3	46.9	48.5	49.9
	K	****	****	****	****	1.26	1.53	1.82	2.12	2.43	2.77	3.12	3.50	3.89	4.31	4.75	5.22	5.70	6.22	6.75	7.32
0.005	%C	****	****	****	****	****	99.3	96.3	92.4	88.5	84.9	81.7	78.8	76.3	74.1	72.1	70.4	68.9	67.6	66.4	65.4
	F	4.467	2.451	1.701	1.312	1.076	0.918	0.807	0.724	0.661	0.612	0.572	0.540	0.513	0.491	0.472	0.456	0.443	0.431	0.420	0.411
	A	4.0	7.4	10.7	13.9	17.0	20.1	23.0	25.8	28.5	31.0	33.4	35.7	37.9	39.9	41.8	43.7	45.4	47.0	48.5	50.0
	K	****	****	****	****	****	1.23	1.46	1.70	1.96	2.23	2.51	2.81	3.13	3.46	3.82	4.19	4.58	4.99	5.42	5.87
0.006	%C	****	****	****	****	****	****	99.9	98.2	95.6	92.8	90.1	87.5	85.2	83.0	81.2	79.5	78.0	76.6	75.4	74.3
	F	5.189	2.890	2.016	1.560	1.282	1.096	0.964	0.866	0.791	0.732	0.685	0.646	0.615	0.588	0.566	0.547	0.531	0.516	0.504	0.493
	A	4.2	7.5	10.8	14.0	17.2	20.2	23.1	25.9	28.6	31.1	33.5	35.8	38.0	40.0	41.9	43.7	45.4	47.1	48.6	50.0
	K	****	****	****	****	****	****	1.23	1.43	1.64	1.86	2.10	2.35	2.62	2.90	3.19	3.50	3.83	4.17	4.53	4.91
0.007	%C	****	****	****	****	****	****	****	****	99.4	97.8	95.9	93.9	91.9	90.1	88.4	86.8	85.4	84.1	83.0	81.9
	F	5.866	3.313	2.325	1.804	1.485	1.271	1.119	1.006	0.919	0.851	0.797	0.752	0.716	0.685	0.659	0.637	0.618	0.602	0.588	0.575
	A	4.3	7.6	10.9	14.2	17.3	20.3	23.2	26.0	28.7	31.2	33.6	35.9	38.0	40.1	42.0	43.8	45.5	47.1	48.6	50.1
	K	****	****	****	****	****	****	****	****	1.41	1.61	1.81	2.02	2.25	2.49	2.75	3.01	3.29	3.59	3.90	4.22
0.008	%C	****	****	****	****	****	****	****	****	****	99.9	99.2	98.0	96.6	95.2	93.9	92.6	91.3	90.2	89.2	88.2
	F	6.502	3.722	2.626	2.044	1.685	1.445	1.273	1.145	1.047	0.970	0.908	0.858	0.816	0.782	0.752	0.727	0.706	0.687	0.671	0.657
	A	4.4	7.8	11.1	14.3	17.4	20.4	23.3	26.1	28.8	31.3	33.7	36.0	38.1	40.1	42.1	43.9	45.6	47.2	48.7	50.1
	K	****	****	****	****	****	****	****	****	****	1.41	1.59	1.78	1.98	2.19	2.41	2.65	2.89	3.15	3.42	3.70
0.010	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	99.9	99.6	99.1	98.6	98.0	97.3	96.7
	F	7.665	4.501	3.208	2.511	2.078	1.786	1.577	1.421	1.301	1.206	1.130	1.068	1.017	0.974	0.938	0.907	0.880	0.857	0.837	0.820
	A	4.7	8.0	11.3	14.5	17.6	20.7	23.6	26.3	29.0	31.5	33.9	36.1	38.3	40.3	42.2	44.0	45.7	47.3	48.8	50.2
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	1.77	1.94	2.13	2.33	2.54	2.75	2.98

CARRIERS	PICKS	ENDS
48	9	10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	****	****	****	****	99.6	95.8	90.9	86.0	81.6	77.7	74.3	71.3	68.8	66.6	64.7	63.0	61.6	60.3	59.2	58.2
	F	4.101	2.179	1.494	1.145	0.935	0.796	0.698	0.626	0.571	0.527	0.493	0.465	0.442	0.422	0.406	0.392	0.380	0.370	0.361	0.353
	A	3.8	7.1	10.4	13.6	16.8	19.8	22.8	25.6	28.2	30.8	33.2	35.5	37.7	39.8	41.7	43.5	45.2	46.9	48.4	49.8
	K	****	****	****	****	1.17	1.42	1.68	1.96	2.26	2.57	2.90	3.25	3.62	4.01	4.42	4.85	5.30	5.78	6.28	6.81
0.004	%C	****	****	****	****	****	****	99.5	97.1	94.1	91.1	88.1	85.4	83.0	80.8	78.9	77.2	75.6	74.3	73.1	72.0
	F	5.281	2.852	1.967	1.513	1.238	1.055	0.926	0.831	0.758	0.701	0.655	0.618	0.588	0.562	0.540	0.522	0.506	0.493	0.481	0.471
	A	3.9	7.3	10.5	13.8	16.9	19.9	22.9	25.7	28.3	30.9	33.3	35.6	37.8	39.8	41.8	43.6	45.3	46.9	48.5	49.9
	K	****	****	****	****	****	****	1.27	1.48	1.70	1.94	2.19	2.45	2.72	3.02	3.33	3.65	3.99	4.35	4.73	5.12
0.005	%C	****	****	****	****	****	****	****	****	99.7	98.4	96.7	94.8	92.9	91.1	89.4	87.9	86.5	85.2	84.1	83.0
	F	6.382	3.502	2.429	1.874	1.536	1.312	1.153	1.035	0.944	0.874	0.817	0.771	0.733	0.701	0.675	0.652	0.632	0.615	0.601	0.588
	A	4.0	7.4	10.7	13.9	17.0	20.1	23.0	25.8	28.5	31.0	33.4	35.7	37.9	39.9	41.8	43.7	45.4	47.0	48.5	50.0
	K	****	****	****	****	****	****	****	****	1.37	1.56	1.76	1.97	2.19	2.42	2.67	2.93	3.21	3.49	3.79	4.11
0.006	%C	****	****	****	****	****	****	****	****	****	****	100.0	99.4	98.5	97.4	96.3	95.2	94.1	93.1	92.2	91.3
	F	7.413	4.128	2.880	2.229	1.831	1.565	1.377	1.237	1.130	1.045	0.978	0.923	0.878	0.840	0.808	0.781	0.758	0.738	0.720	0.705
	A	4.2	7.5	10.8	14.0	17.2	20.2	23.1	25.9	28.6	31.1	33.5	35.8	38.0	40.0	41.9	43.7	45.4	47.1	48.6	50.0
	K	****	****	****	****	****	****	****	****	****	****	1.47	1.65	1.83	2.03	2.23	2.45	2.68	2.92	3.17	3.44
0.007	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	100.0	99.7	99.2	98.6	98.0	97.4	96.8
	F	8.379	4.733	3.321	2.577	2.121	1.816	1.599	1.437	1.313	1.216	1.138	1.075	1.023	0.979	0.942	0.910	0.883	0.860	0.839	0.822
	A	4.3	7.6	10.9	14.2	17.3	20.3	23.2	26.0	28.7	31.2	33.6	35.9	38.0	40.1	42.0	43.8	45.5	47.1	48.6	50.1
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	1.74	1.92	2.11	2.31	2.51	2.73	2.95
0.008	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	100.0	99.8	99.6
	F	9.288	5.318	3.751	2.920	2.408	2.064	1.818	1.636	1.496	1.386	1.298	1.226	1.166	1.117	1.075	1.039	1.008	0.982	0.958	0.938
	A	4.4	7.8	11.1	14.3	17.4	20.4	23.3	26.1	28.8	31.3	33.7	36.0	38.1	40.1	42.1	43.9	45.6	47.2	48.7	50.1
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	2.21	2.39	2.59
0.010	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
	F	10.951	6.430	4.583	3.587	2.969	2.551	2.252	2.029	1.858	1.723	1.614	1.526	1.453	1.391	1.340	1.295	1.257	1.225	1.196	1.171
	A	4.7	8.0	11.3	14.5	17.6	20.7	23.6	26.3	29.0	31.5	33.9	36.1	38.3	40.3	42.2	44.0	45.7	47.3	48.8	50.2
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****

CARRIERS	PICKS	ENDS
48	15	4

STR.DIA. — DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	******	98.6	85.1	73.0	64.1	57.7	53.0	49.4	46.7	44.6	42.9	41.5	40.4	39.5	38.7	38.1	37.5	37.0	36.6	36.3
	F	1.647	0.883	0.615	0.480	0.401	0.350	0.314	0.289	0.270	0.255	0.244	0.235	0.228	0.222	0.217	0.213	0.209	0.206	0.204	0.202
	A	6.3	11.8	17.0	22.0	26.7	31.0	35.0	38.6	41.8	44.8	47.5	50.0	52.2	54.2	56.0	57.7	59.2	60.7	62.0	63.1
	K	******	1.18	1.78	2.42	3.13	3.89	4.74	5.66	6.68	7.78	8.98	10.27	11.67	13.16	14.76	16.46	18.26	20.17	22.18	24.30
0.004	%C	******	******	96.4	86.7	78.0	71.2	66.1	62.0	58.9	56.4	54.4	52.8	51.5	50.4	49.5	48.7	48.0	47.5	47.0	46.5
	F	2.121	1.157	0.810	0.635	0.531	0.464	0.417	0.384	0.359	0.340	0.325	0.313	0.303	0.296	0.289	0.284	0.279	0.275	0.272	0.269
	A	6.5	12.0	17.2	22.2	26.9	31.2	35.1	38.7	42.0	44.9	47.6	50.0	52.3	54.3	56.1	57.8	59.3	60.7	62.0	63.2
	K	******	******	1.35	1.84	2.37	2.94	3.58	4.28	5.04	5.87	6.77	7.75	8.80	9.92	11.12	12.40	13.75	15.19	16.70	18.29
0.005	%C	******	******	******	95.5	88.4	82.1	76.9	72.8	69.5	66.8	64.7	62.9	61.4	60.2	59.2	58.3	57.6	56.9	56.4	55.9
	F	2.564	1.421	1.001	0.787	0.660	0.577	0.520	0.478	0.448	0.424	0.406	0.391	0.379	0.369	0.361	0.354	0.349	0.344	0.340	0.336
	A	6.7	12.2	17.4	22.4	27.0	31.3	35.3	38.8	42.1	45.0	47.7	50.1	52.3	54.3	56.2	57.8	59.4	60.8	62.1	63.2
	K	******	******	******	1.49	1.91	2.38	2.89	3.44	4.06	4.72	5.45	6.23	7.07	7.97	8.94	9.96	11.05	12.20	13.41	14.68
0.006	%C	******	******	******	99.6	95.5	90.3	85.7	81.7	78.5	75.8	73.6	71.7	70.2	68.9	67.9	66.9	66.1	65.5	64.9	64.4
	F	2.979	1.676	1.188	0.937	0.787	0.689	0.621	0.572	0.536	0.508	0.486	0.468	0.454	0.443	0.433	0.425	0.418	0.412	0.407	0.403
	A	6.9	12.4	17.6	22.6	27.2	31.5	35.4	39.0	42.2	45.2	47.8	50.2	52.4	54.4	56.2	57.9	59.4	60.8	62.1	63.3
	K	******	******	******	1.25	1.61	2.00	2.42	2.89	3.40	3.96	4.56	5.22	5.92	6.67	7.48	8.34	9.24	10.20	11.21	12.28
0.007	%C	******	******	******	******	99.2	96.0	92.3	88.8	85.8	83.3	81.2	79.4	77.8	76.6	75.5	74.5	73.7	73.0	72.4	71.9
	F	3.369	1.923	1.370	1.084	0.913	0.800	0.722	0.666	0.624	0.591	0.566	0.546	0.529	0.516	0.505	0.495	0.488	0.481	0.475	0.470
	A	7.2	12.6	17.8	22.8	27.4	31.7	35.6	39.1	42.3	45.3	47.9	50.3	52.5	54.5	56.3	58.0	59.5	60.9	62.2	63.3
	K	******	******	******	******	1.39	1.72	2.09	2.49	2.93	3.41	3.93	4.50	5.10	5.75	6.44	7.17	7.95	8.78	9.65	10.56
0.008	%C	******	******	******	******	******	99.2	96.8	94.2	91.7	89.4	87.4	85.8	84.3	83.1	82.1	81.1	80.4	79.7	79.1	78.6
	F	3.735	2.161	1.549	1.229	1.037	0.910	0.823	0.759	0.711	0.674	0.646	0.623	0.604	0.589	0.576	0.566	0.557	0.549	0.543	0.537
	A	7.4	12.8	18.1	23.0	27.6	31.8	35.7	39.2	42.5	45.4	48.0	50.4	52.6	54.6	56.4	58.0	59.5	60.9	62.2	63.4
	K	******	******	******	******	******	1.52	1.84	2.20	2.58	3.00	3.46	3.95	4.48	5.05	5.66	6.30	6.99	7.71	8.47	9.27
0.010	%C	******	******	******	******	******	******	******	99.7	98.7	97.4	96.2	95.0	93.9	93.0	92.1	91.4	90.7	90.1	89.6	89.2
	F	4.406	2.616	1.895	1.513	1.281	1.128	1.021	0.943	0.885	0.840	0.805	0.776	0.754	0.735	0.719	0.706	0.695	0.686	0.678	0.671
	A	7.8	13.3	18.5	23.4	27.9	32.1	36.0	39.5	42.7	45.6	48.2	50.6	52.8	54.7	56.5	58.2	59.7	61.0	62.3	63.5
	K	******	******	******	******	******	******	******	1.78	2.09	2.43	2.80	3.20	3.62	4.08	4.57	5.09	5.64	6.22	6.83	7.47

	CARRIERS 48	PICKS 15	ENDS 7

STR.DIA. — DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C				97.4	91.1	84.9	79.7	75.5	72.1	69.4	67.2	65.4	63.9	62.6	61.5	60.6	59.9	59.2	58.6	58.1
	F	2.882	1.546	1.076	0.840	0.701	0.612	0.550	0.505	0.472	0.447	0.427	0.411	0.399	0.388	0.380	0.373	0.367	0.361	0.357	0.353
	A	6.3	11.8	17.0	22.0	26.7	31.0	35.0	38.6	41.8	44.8	47.5	50.0	52.2	54.2	56.0	57.7	59.2	60.7	62.0	63.1
	K				1.39	1.79	2.23	2.71	3.24	3.82	4.45	5.13	5.87	6.67	7.52	8.43	9.41	10.44	11.52	12.67	13.88
0.004	%C					99.5	96.5	92.7	89.2	86.2	83.6	81.4	79.6	78.0	76.7	75.6	74.6	73.8	73.1	72.5	72.0
	F	3.712	2.025	1.417	1.111	0.929	0.812	0.730	0.672	0.628	0.595	0.569	0.548	0.531	0.517	0.506	0.496	0.488	0.482	0.476	0.471
	A	6.5	12.0	17.2	22.2	26.9	31.2	35.1	38.7	42.0	44.9	47.6	50.0	52.3	54.3	56.1	57.8	59.3	60.7	62.0	63.2
	K					1.35	1.68	2.05	2.44	2.88	3.35	3.87	4.43	5.03	5.67	6.35	7.08	7.86	8.68	9.54	10.45
0.005	%C							99.2	97.3	95.3	93.3	91.6	90.0	88.7	87.5	86.5	85.6	84.8	84.1	83.5	83.0
	F	4.487	2.487	1.752	1.377	1.155	1.010	0.910	0.837	0.783	0.742	0.710	0.684	0.663	0.646	0.632	0.620	0.610	0.602	0.594	0.588
	A	6.7	12.2	17.4	22.4	27.0	31.3	35.3	38.8	42.1	45.0	47.7	50.1	52.3	54.3	56.2	57.8	59.4	60.8	62.1	63.2
	K							1.65	1.97	2.32	2.70	3.11	3.56	4.04	4.56	5.11	5.69	6.31	6.97	7.66	8.39
0.006	%C									99.6	98.8	97.8	96.7	95.8	94.9	94.1	93.4	92.8	92.2	91.8	91.3
	F	5.213	2.933	2.078	1.639	1.377	1.206	1.087	1.002	0.938	0.889	0.850	0.820	0.795	0.775	0.758	0.744	0.732	0.722	0.713	0.705
	A	6.9	12.4	17.6	22.6	27.2	31.5	35.4	39.0	42.2	45.2	47.8	50.2	52.4	54.4	56.2	57.9	59.4	60.8	62.1	63.3
	K									1.94	2.26	2.61	2.98	3.38	3.81	4.27	4.76	5.28	5.83	6.41	7.02
0.007	%C											100.0	99.8	99.5	99.1	98.6	98.2	97.8	97.5	97.2	96.8
	F	5.895	3.365	2.398	1.897	1.597	1.401	1.264	1.165	1.091	1.035	0.990	0.955	0.926	0.903	0.883	0.867	0.853	0.841	0.831	0.823
	A	7.2	12.6	17.8	22.8	27.4	31.7	35.6	39.1	42.3	45.3	47.9	50.3	52.5	54.5	56.3	58.0	59.5	60.9	62.2	63.3
	K											2.25	2.57	2.91	3.28	3.68	4.10	4.55	5.02	5.51	6.04
0.008	%C																100.0	99.9	99.8	99.7	99.6
	F	6.536	3.782	2.711	2.151	1.814	1.593	1.439	1.328	1.244	1.180	1.130	1.090	1.057	1.031	1.009	0.990	0.974	0.961	0.950	0.940
	A	7.4	12.8	18.1	23.0	27.6	31.8	35.7	39.2	42.5	45.4	48.0	50.4	52.6	54.6	56.4	58.0	59.5	60.9	62.2	63.4
	K																3.60	3.99	4.41	4.84	5.30
0.010	%C																				
	F	7.711	4.578	3.316	2.648	2.242	1.974	1.786	1.650	1.548	1.470	1.408	1.359	1.319	1.286	1.259	1.236	1.217	1.200	1.186	1.174
	A	7.8	13.3	18.5	23.4	27.9	32.1	36.0	39.5	42.7	45.6	48.2	50.6	52.8	54.7	56.5	58.2	59.7	61.0	62.3	63.5
	K																				

CARRIERS 48 PICKS 15 ENDS 10

DIAMETER OVER DIELECTRIC

STR.DIA.		0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	1.000
0.003	%C	****	****	****	****	****	98.4	95.4	92.3	89.4	86.9	84.8	83.0	81.5	80.2	79.1	78.1	77.3	76.6	76.0	75.4
	F	4.117	2.208	1.536	1.200	1.002	0.874	0.785	0.722	0.675	0.638	0.610	0.588	0.570	0.555	0.543	0.532	0.524	0.516	0.510	0.504
	A	6.3	11.8	17.0	22.0	26.7	31.0	35.0	38.6	41.8	44.8	47.5	50.0	52.2	54.2	56.0	57.7	59.2	60.7	62.0	63.1
	K	****	****	****	****	****	1.56	1.90	2.27	2.67	3.11	3.59	4.11	4.67	5.27	5.90	6.58	7.30	8.07	8.87	9.72
0.004	%C	****	****	****	****	****	****	****	99.8	98.9	97.7	96.5	95.3	94.2	93.2	92.3	91.5	90.9	90.3	89.7	89.3
	F	5.303	2.892	2.025	1.587	1.328	1.159	1.043	0.960	0.897	0.850	0.812	0.783	0.759	0.739	0.723	0.709	0.698	0.688	0.680	0.672
	A	6.5	12.0	17.2	22.2	26.9	31.2	35.1	38.7	42.0	44.9	47.6	50.0	52.3	54.3	56.1	57.8	59.3	60.7	62.0	63.2
	K	****	****	****	****	****	****	****	1.71	2.02	2.35	2.71	3.10	3.52	3.97	4.45	4.96	5.50	6.07	6.68	7.31
0.005	%C	****	****	****	****	****	****	****	****	****	****	****	99.9	99.7	99.4	99.1	98.7	98.4	98.0	97.7	97.4
	F	6.410	3.553	2.502	1.967	1.649	1.442	1.299	1.196	1.119	1.060	1.014	0.977	0.947	0.923	0.903	0.886	0.872	0.859	0.849	0.840
	A	6.7	12.2	17.4	22.4	27.0	31.3	35.3	38.8	42.1	45.0	47.7	50.1	52.3	54.3	56.2	57.8	59.4	60.8	62.1	63.2
	K	****	****	****	****	****	****	****	****	****	****	****	2.49	2.83	3.19	3.57	3.98	4.42	4.88	5.36	5.87
0.006	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
	F	7.448	4.190	2.969	2.342	1.967	1.723	1.553	1.431	1.340	1.269	1.215	1.171	1.136	1.107	1.083	1.062	1.045	1.031	1.018	1.008
	A	6.9	12.4	17.6	22.6	27.2	31.5	35.4	39.0	42.2	45.2	47.8	50.2	52.4	54.4	56.2	57.9	59.4	60.8	62.1	63.3
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
0.007	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
	F	8.421	4.807	3.426	2.711	2.282	2.001	1.806	1.665	1.559	1.478	1.415	1.364	1.323	1.290	1.262	1.239	1.219	1.202	1.188	1.175
	A	7.2	12.6	17.8	22.8	27.4	31.7	35.6	39.1	42.3	45.3	47.9	50.3	52.5	54.5	56.3	58.0	59.5	60.9	62.2	63.3
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
0.008	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
	F	9.337	5.404	3.872	3.073	2.592	2.276	2.056	1.897	1.778	1.686	1.614	1.557	1.511	1.473	1.441	1.415	1.392	1.373	1.357	1.342
	A	7.4	12.8	18.1	23.0	27.6	31.8	35.7	39.2	42.5	45.4	48.0	50.4	52.6	54.6	56.4	58.0	59.5	60.9	62.2	63.4
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
0.010	%C	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
	F	11.016	6.541	4.738	3.783	3.202	2.819	2.552	2.358	2.212	2.100	2.012	1.941	1.884	1.837	1.798	1.766	1.738	1.715	1.694	1.677
	A	7.8	13.3	18.5	23.4	27.9	32.1	36.0	39.5	42.7	45.6	48.2	50.6	52.8	54.7	56.5	58.2	59.7	61.0	62.3	63.5
	K	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****